NASA
Technical
Paper
2751

August 1987

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NASA

NASA Technical Paper 2751

1987

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Summary

A study was conducted to explore the potential of quasi-hybrid rockets for advanced Earth-to-orbit applications. Thermochemical calculations were performed for three quasi-hybrid concepts: a liquid-hydrogen-injected solid rocket booster; a liquid-hydrogen-injected solid rocket booster with a solids composition change; and an aluminum/liquid-hydrogen-slurry-injected solid rocket booster. With the current space shuttle solid rocket boosters as a reference point, calculations were conducted at a nominal chamber pressure of 4.233 MN/m^2 (614 psia), and ideal expansion to an area ratio of 7.72.

All three quasi-hybrid systems offer higher specific impulse when compared with the current theoretical performance of the space shuttle solid rocket boosters. Addition of liquid hydrogen to polybutadiene–acrylic acid–acrylonitrile (PBAN) solid propellant increases theoretical specific impulse by 42.6 sec so that 294.3-sec theoretical specific impulse is achievable when 23 wt % of the total propellant (solid plus liquid) is liquid hydrogen. To optimize performance, the aluminum loading in the solid propellant must be increased in proportion to the quantity of liquid hydrogen added. The shuttle solid rocket boosters currently use a PBAN solid propellant blend containing 16 wt % aluminum and 69.84 wt % ammonium perchlorate. When 23 wt % of the total propellant is liquid hydrogen, the solid propellant should contain 36 wt % aluminum and 49.84 wt % ammonium perchlorate for a maximum theoretical performance of 321.8 sec. As an alternate to varying solid propellant composition, an aluminum/liquid hydrogen slurry can be added to supply the additional aluminum required for optimum performance. Maximum theoretical specific impulse (325.9 sec) is achieved when 45 wt % of the total propellant is slurry and 50 wt % of the slurry is aluminum. This represents a 74.2-sec specific impulse improvement over PBAN solid propellant.

Additional calculations were conducted to estimate the thrust increase and required tankage volumes associated with the addition of liquid hydrogen or aluminum/liquid hydrogen slurry to space-shuttle-size solid rocket boosters. Tankage volume requirements are excessively large to achieve peak theoretical specific impulse. Vehicle constraints will limit fluid augmentations to a few weight percent, therefore limiting specific impulse advantages of the quasi-hybrid systems. Mission analysis is required to determine any actual improvements in vehicle performance by using quasi-hybrid rockets for Earth-to-orbit vehicles.

Finally, safety and technology issues pertinent to quasi-hybrid rockets were evaluated to assess the practicality of the concept for Earth-to-orbit applications. The quasi-hybrid rocket offers some practical advantages over conventional all-solid and all-liquid propellant rockets. However, problems with accurate calibration and reliable operation, safety problems, and lack of any apparent advantage over solid rockets for combustion termination during operation make quasi-hybrid rockets an inappropriate choice for advanced shuttle derivatives for near-term Earth-to-orbit booster applications.

Introduction

The desire for alternatives to the current space shuttle solid rocket boosters has initiated interest in hybrid and pressure-fed booster configurations for advanced Earth-to-orbit vehicles. An advanced hybrid system can potentially provide the performance increase necessary to reduce space shuttle main engine (SSME) 109 percent power level operation and offers the possibility for safe termination and shuttle abort during booster operation. Therefore a study was initiated to explore the potential of one type of hybrid rocket, the quasi-hybrid rocket, for advanced Earth-to-orbit vehicles. Thermochemical performance calculations for three quasi-hybrid rocket concepts and an evaluation of relevant safety and technology issues were conducted. The current space shuttle solid rocket boosters (SRB's) were used as a reference point for the study. This report presents the theoretical performance of three quasi-hybrid rocket concepts with corresponding thrust augmentation, fluid mass flow rates, and fluid tankage volumes required for space-shuttle-size boosters. The results of an evaluation of quasi-hybrid rockets for Earth-to-orbit boosters based on important operational and safety characteristics are also presented.

There are many kinds of hybrid rockets just as there are many kinds of liquid propellant and solid propellant rockets. Hybrid rockets are categorized by whether the oxidizer or fuel is liquid and by the design configuration of the rocket. It should be noted that use of the term "hybrid rocket" in this report refers to a broad class of rockets which use a combination of solid and liquid propellants. Specific kinds of hybrid rockets such as conventional hybrid rockets, reverse hybrid rockets, and quasi-hybrid rockets, which are discussed in the text, will be identified. A conventional hybrid rocket uses a liquid oxidizer and solid fuel. The oxidizer is sprayed in at the head end of a solid cylindrical fuel grain and can be either a storable or cryogenic liquid depending on the specific impulse needed or other requirements of the application. When the fuel is a liquid and the oxidizer is a solid, the rocket is called a reverse hybrid. A liquid oxidizer/liquid fuel/solid fuel rocket is called a tribrid. Finally, a solid oxidizer/solid fuel rocket augmented by a liquid fuel is called a quasi-hybrid rocket (ref. 1). The four hybrid concepts are depicted in figure 1. The concepts analyzed in this study are quasi-hybrid since they involve a conventional solid rocket motor which contains solid oxidizer and solid fuel augmented with a liquid fuel or a liquid plus solid fuel combination (slurry).

Hybrid rockets possess some of the advantages of both liquid and solid rocket engines, thereby offering a performance typically between the two. A high energy-density solid propellant, characterized by simple handling and desirable physical properties, can be employed with a liquid propellant which is easily regulated and offers the possibility of intermittent operation. The major advantages hybrid rockets can have relative to liquid or solid rockets include: low cost; propellant combinations offering good specific impulse and high density; the simplicity of the solid grain propellant systems; a liquid for regenerative cooling of engine parts under high thermal load; thrust modulation; the possibility of start-stop-restart capability; and good storability traits (ref. 2). These advantages are why hybrid rocket systems are being considered as alternatives to the solid rocket booster systems currently used with the Space Shuttle Space Transportation System (STS).

Present experimental and developmental effort is being conducted in the field of hybrid rocketry. The American Rocket Company (AMROC) is developing its Industrial Launch Vehicle (ILV), a commercial expendable launcher, with 19 nearly identical hybrid rocket engines to place a 3000-lb payload into polar orbit or a 4000-lb payload into equatorial orbit. Three test flights of the ILV are planned for early 1988, and commercial launches will begin in late 1988 (ref.3). The Air Force Astronautics Laboratory (AFAL) initiated an experimental study in 1986 to demonstrate thrust augmentation of its 70-lb Ballistic Test and Evaluation System (BATES) motor by the injection of gaseous hydrogen. The tests are designed to evaluate the following: (1) the effect of residence time (head-end/aft-end injection) and particulate interaction on performance, (2) combustion instability with pulsed mode hydrogen injection, and (3) the feasibility of thrust vector control and reduced throat ablation rate (ref. 4).

Quasi-hybrid rockets were of particular interest in this analysis since one potential near-term application is hydrogen augmentation of the space shuttle solid rocket boosters. However, quasi-hybrid rockets posses unique operational and safety characteristics compared to other types of hybrid rocket systems. Therefore an evaluation of safety and technology areas relevant to quasi-hybrid rockets was conducted in addition to thermochemical performance calculations in order to assess the practically of quasi-hybrid rockets for advanced Earth-to-orbit applications.

Three quasi-hybrid rocket concepts were considered in the study. Table I contains data on the Space Shuttle Space Transportation System relevant to the analysis. More detailed information is available in references 5 and 6. The shuttle SRB's were used as a reference point with which to compare the performance of the quasi-hybrid systems and as a basis for the calculation of liquid or slurry quantities and tankage

TABLE I.—SPACE SHUTTLE SPACE TRANSPORTATION SYSTEM DATA

(a) PBAN solid propellant composition

Propellant component	Content, wt %	Density, g/cm^3	Reference enthalpy, kJ/mol
Ammonium perchlorate	69.84	1.95	−295.8
Aluminum	16.00	2.70	0.0
Binder	12.04	.93	−50.2
Curing agent	1.96	1.13	−118.4
Burning rate catalyst	.16	5.12	−825.5

(b) Space shuttle propulsion system and vehicle data

Area ratio	7.72
Nominal burn time, sec	123.4
Nominal chamber pressure, MN/m^2 (psia)	4.233 (614)
SRB exit diameter, cm (in.)	375 (148)
Liquid oxygen external tank volume, m^3 (ft^3)	541 (19 103)
Liquid hydrogen external tank volume, m^3 (ft^3)	1 450 (51 201)
Total external tank volume, m^3 (ft^3)	1 991 (70 304)
SSME sea level thrust (109 % power level), MN (MlbF)	1.820 (0.409)

volumes required to augment large solid rocket boosters for Earth-to-orbit applications. The three quasi-hybrid concepts are shown in figure 2. In concept 1 (fig. 2(a)) liquid hydrogen augments a solid rockets motors using PBAN solid propellant (polybutadiene–acrylic acid–acrylonitrile solid propellent. This is the same propellant used in the shuttle SRB's. Concept 2 (fig. 2(b)) is similar to concept 1 except the aluminum-to-ammonium perchlorate ratio in the solid propellant is proportioned to optimize specific impulse of the quasi-hybrid rocket. In concept 3 (fig. 2(c)) an aluminum/liquid hydrogen slurry is added to the PBAN solid propellant motor. With this system more aluminum can be added to the combustion process to optimize specific impulse without having to change solid propellant composition.

For the analytical study, Gordon and McBride's Computer Program for Calculation of Complex Equilibrium Composition, Rocket Performance, Incident and Reflected Shocks, and Chapman-Jouguet Detonations (CEC computer program) (ref. 7) was used to generate specific impulse values for the candidate quasi-hybrid concepts over a range of propellant compositions. The program calculated these theoretical rocket parameters by assuming equilibrium composition during ideal expansion to an area ratio of 7.72 for a nominal 4.233-MN/m^2 (614-psia) chamber pressure. In the analysis, the relative composition of the solid constituents was kept constant while the amount of liquid or slurry was increased. In this way the specific impulse of a quasi-hybrid rocket could be calculated as a function of the quantity of liquid or slurry added to a solid propellent motor. It must be noted that the performance values reported in this report are strictly theoretical and represent the maximum specific impulse thermochemically achievable from a perfectly expanded system. Actual specific impulse values will characteristically be 8 to 10 percent lower than theoretical after taking into account realistic losses caused by combustion inefficiencis, chemical kinetic effects, two-phase flow, nozzle divergence, boundary layer effects, and nozzle back-pressure (ref. 8). An analytical prediction of these losses was beyond the scope of this analysis.

Thermochemical Calculations

Thermochemical calculations were conducted by using the CEC computer program to determine the theoretical specific impulse for the three candidate quasi-hybrid concepts as follows: (1) liquid-hydrogen-injected solid rocket booster, (2) liquid-hydrogen-injected solid rocket booster with a solids composition change, and (3) aluminum/liquid-hydrogen-slurry-injected solid rocket booster. The assumptions of this study were a shifting equilibrium composition and an ideal expansion from a nominal chamber pressure of 4.233 MN/m^2 (614 psia) to an area ratio of 7.72. Chemical equilibrium was based on the minimization of Gibbs free energy of the chemically reacting system. The area ratio and chamber pressure used are characteristic values based on the space shuttle SRB's.

The range of propellant composition used in the CEC program to calculate the theoretical specific impulse of each quasi-hybrid concept is presented in appendix A. Variations in total propellant composition unique to each concept were made by attempting to simulate the performance of each quasi-hybrid system. For the liquid-hydrogen-injected solid rocket booster the PBAN solid propellant composition was maintained constant relative to the total (solid plus liquid) propellant composition. In the analysis of the liquid-hydrogen-injected solid rocket booster with a solids composition change, the aluminum-to-ammonium perchlorate ratio was varied while maintaining a constant binder, curing agent, and burning rate catalyst composition. Finally, with the aluminum/liquid-hydrogen-slurry-injected solid rocket booster the PBAN solid propellant composition was maintained constant relative to the total (solid plus slurry) propellant composition. In addition, the ratio of aluminum to liquid hydrogen in the slurry was incrementally varied to establish the optimum specific impulse in terms of slurry quantity and composition.

The following sections of this report discuss the results of the analysis by addressing each quasi-hybrid booster concept individually. Figures 3 to 16 summarize the thermochemical results in terms of theoretical specific impulse, augmenting fluid mass flow rate and volume, and thrust. Specific impulse is a computed parameter of the CEC program. Augmenting fluid mass flow rate, tankage volume requirements, and thrust of a quasi-hybrid rocket comparable in size to a space shuttle SRB are calculated with the equations in appendix B and are tabulated in appendix C. Numerical values relevant to these equations are noted in figures 3 to 16 for easy reference.

Peak theoretical specific impulse values for all the quasi-hybrid concepts analyzed are compared to the specific impulse of PBAN solid propellant in table II. Also given are the propellant compositions for peak performance. The quasi-hybrid rockets analyzed offer large specific impulse advantages over conventional solid propellant rockets and appear attractive based solely on specific impulse. However, the feasibility of quasi-hybrid rockets for large booster applications can not be judged solely on thermochemical performance. Vehicle constraints, safety concerns, and technology level must also be considered. This is the subject of further discussion in this paper.

Liquid-Hydrogen-Injected Solid Rocket Booster

A preliminary analysis was conducted to determine the best augmenting fluid for the quasi-hybrid rockets. Augmenting fluids considered were RP-1, propane, liquid methane, liquid oxygen, hydrazine, and liquid hydrogen. The CEC program was used to calculate theoretical specific impulse of a PBAN solid propellant rocket augmented by each liquid fuel as a function of the amount of liquid fuel added. Calculations were conducted for ideal expansion from a chamber pressure of

TABLE II.—PEAK THEORETICAL SPECIFIC IMPULSE OF QUASI-HYBRID ROCKET CONCEPTS

Quasi-hybrid concept	Solids composition,[a] wt % of solid propellant		Composition of augmenting fluid, wt %		Fluid augmentation, wt % of total propellant	Specific impulse I_{sp}, sec
	Aluminum	Ammonium perchlorate	Liquid hydrogen	Aluminum		
PBAN solid rocket (baseline)	16.0	69.84	0.0	0.0	0.0	251.7
Optimum PBAN solid rocket	21.0	64.84	0.0	0.0	0.0	252.8
Liquid-hydrogen-injected solid rocket	16.0	69.84	100.0	0.0	23.0	294.3
Liquid-hydrogen-injected solid rocket with solids composition change	36.0	49.84	100.0	0.0	23.0	321.8
Aluminum/liquid-hydrogen-slurry-injected solid rocket	16.0	69.84	50.0	50.0	45.0	325.9

[a]Constant PBAN binder composition of 12.04 wt % binder, 1.96 wt % curing agent, and 0.16 wt % burning rate catalyst.

4.233 MN/m^2 (614 psia) to an area ratio of 7.72. Figure 3 presents the peak theoretical specific impulse achievable by augmenting the solid rocket with each liquid fuel. The percentage of augmenting fuel is the amount of liquid added as a percentage of total propellant (solid plus liquid). PBAN solid propellant delivers 251.7-sec theoretical specific impulse. Addition of the liquid hydrocarbon fuels elevates the specific impulse of the system by only a few seconds. Liquid oxygen addition increases specific impulse by 4.1 sec, and hydrazine addition results in a 9.2-sec increase. However, liquid hydrogen augmentation delivers 42.6 additional seconds specific impulse compared with PBAN solid propellant. Hydrogen addition dramatically improves specific impulse because it acts to lower the molecular weight of the combustion products while increasing the energy (temperature) of the system. For these reasons and because quasi-hybrid rockets can be considered a potential propulsion option for an advanced STS booster, hydrogen was chosen as the augmenting fluid for analysis with the quasi-hybrid concepts.

The complete results of thermochemical calculations on the liquid-hydrogen-injected solid rocket booster are shown in figure 4. Peak theoretical specific impulse of 294.3 sec occurs when 23 wt % of the total propellant is liquid hydrogen. A SRB-size motor with 23 wt % hydrogen augmentation would require a liquid mass flow rate of 1159.6 kg/sec (2556.4 lb/sec) and hydrogen tankage volumes of 2016 m^3 (71 186 ft^3) for a nominal mission (123.4 sec burn). This liquid augmentation would elevate the thrust of the booster to 14.550 MN (3.271 Mlbf). Figures 5 and 6 show liquid hydrogen mass-flow rate and tankage volume requirements, respectively. Figure 7 shows the thrust variation of the booster with liquid hydrogen addition.

Peak specific impulse of the liquid-hydrogen-injected solid rocket booster could not be practically achieved in STS booster applications because of the excessive liquid hydrogen tankage volume requirements. To achieve peak specific impulse of 294.3 sec at 23 wt % hydrogen addition, a quasi-hybrid rocket replacement for a SRB requires an additional 566 m^3 (19 986 ft^3) of liquid hydrogen than is currently available in the STS external tank. Gains in specific impulse can be achieved by using hydrogen augmentations less than 23 wt %. At 5 wt % liquid hydrogen addition, a theoretical specific impulse of 276.5 sec is achievable. This 24.8-sec specific impulse increase can be realized for a quasi-hybrid booster by using a hydrogen mass flow rate of 204.3 kg/sec (450.4 lb/sec). A hydrogen tankage volume of 355 m^3 (12 535 ft^3) would be required. The corresponding thrust is 11.079 MN (2.491 Mlbf). As a reference point, this increase in thrust over the shuttle SRB's represents 27 percent of the sea level thrust of the three SSME's at 109 percent power level operation. Mission analysis is required to determine if SRB replacement by a quasi-hybrid booster could yield improvements in STS vehicle performance. Such analysis was beyond the scope of this study.

Liquid-Hydrogen-Injected Solid Rocket Booster with a Solids Composition Change

The optimum solid propellant composition varies as liquid hydrogen is added to the system. Therefore, the second quasi-hybrid concept analyzed was a liquid-hydrogen-injected solid rocket booster with a solids composition change. A preliminary analysis was conducted to determine the optimum aluminum composition in a PBAN solid propellant. The aluminum content in the solid propellant was varied from 12 to 40 wt % while holding the binder, curing agent, and burning rate catalyst composition constant. Figure 8 shows the variation in specific impulse with aluminum content. Performance is optimized with 21 wt % aluminum in the solid propellant. Performance is slightly compromised with the solid PBAN propellant used in the shuttle SRB's which contains only 16 wt % aluminum in order to achieve desirable thermal and mechanical grain properties and facilitate processing of the propellant.

Figure 9 shows the results of analysis on the liquid-hydrogen-injected rocket with varying solids composition. The optimum aluminum content varies as hydrogen is added to the solid propellant. Peak theoretical specific impulse of 321.8 sec occurs when 23 wt % of the total propellant is liquid hydrogen and 36 wt % of the solid propellant is aluminum. Liquid hydrogen mass-flow rate and tankage requirements for the quasi-hybrid concept are shown in figures 10 and 11, respectively. For these calculations, the solids burning rate was assumed constant at the burning rate of PBAN solid propellant in the SRB's (0.366 in/sec). However, in actual application the burning rate is dependent on many variables including the time variation of the chamber pressure, the solid propellant composition, initial temperature of the propellant, velocity of the gas flow parallel to the burning surface, motor motion, combustion gas temperature, and motor configuration. Figure 12 shows the increase in thrust that results from augmenting the solid booster with liquid hydrogen and changing the density of the solid propellant by varying the aluminum content. It is clear from these figures that excessive tankage volumes are required for large Earth-to-orbit size boosters with liquid hydrogen augmentations of more than a few weight percent.

The performance calculations for this quasi-hybrid rocket were conducted by varying the aluminum and ammonium perchlorate content in the solid propellant while holding the binder, curing agent, and burning rate catalyst composition constant. An investigation was conducted to determine if such solid propellant compositions would be acceptably processable. The solid propellant is constrained by a minimum binder level for adequate processability to avoid a propellant mix that is too grainy or stiff. An empirical correlation has been developed which relates the relative volumes of solids and liquids in the propellant mix to the processability (ref. 9). Considering the binder, curing agent, and burning rate catalyst as liquids, and the ammonium perchlorate and aluminum as solids, the processability factor is stated in terms of the volume percent solid (*VPS*) or the solid-to-liquid (*S/L*) volume ratio as follows:

$$VPS = \frac{\dfrac{X}{\rho_{Al}} + \dfrac{X}{\rho_{\text{ammonium perchlorate}}}}{\dfrac{1}{\rho_{\text{bulk}}}} \times 100$$

$$\frac{S}{L} = \frac{VPS}{100 - VPS}$$

Values for the processability factor and processability criteria are shown in tables III and IV, respectively. By varying the aluminum content from 0 to 40 wt % and ammonium perchlorate content from 69.84 to 29.84 wt %, the processability factor ranges from 2.99 to 2.60. These values of the *S/L* volume ratio are defined as normal processability, and hence, are acceptable from a processability viewpoint. However, internal ballistic properties, mechanical properties, hazard properties and storage stability must also be considered when varying the grain composition of a solid propellant.

TABLE III.—PROCESSABILITY FACTORS OF PBAN SOLID PROPELLANT WITH VARYING ALUMINUM CONTENT

[Constant PBAN binder composition (14.16 wt % total propellant) of 12.04 wt% binder, 1.96 wt% curing agent, 0.16 wt% burning rate catalyst.]

Aluminum, wt %	Ammonium perchlorate, wt%	Solid bulk density,[a] g/cm^3	Vol % solid, *VPS*	Solid-to-liquid volume ratio
0	85.84	1.7026	74.95	2.99
2	83.84	1.7109	74.83	2.99
4	81.84	1.7193	74.70	2.95
6	79.84	1.7278	74.58	2.93
8	77.84	1.7363	74.45	2.91
10	74.84	1.7450	74.33	2.90
12	73.84	1.7537	74.20	2.88
14	71.84	1.7625	74.07	2.86
16	69.84	1.7714	73.94	2.84
18	67.84	1.7804	73.81	2.82
20	65.84	1.7894	73.67	2.80
22	63.84	1.7986	73.54	2.78
24	61.84	1.8079	73.40	2.76
26	59.84	1.8172	73.26	2.74
28	57.84	1.8267	73.13	2.72
30	55.84	1.8362	72.98	2.70
32	53.84	1.8459	72.84	2.68
34	51.84	1.8557	72.70	2.66
36	49.84	1.8655	72.55	2.64
38	47.84	1.8755	72.41	2.62
40	45.84	1.8856	72.26	2.60

[a]Ammonium perchlorate (solid), 1.95 g/cm^3; aluminum (solid), 2.70 g/cm^3; binder (liquid), 0.93 g/cm^3; curing agent (liquid), 1.13 g/cm^3; burning rate catalyst (liquid), 5.12 g/cm^3.

TABLE IV.—PROCESSABILITY CRITERIA

[Reproduced from reference 9.]

Solid to liquid	Characteristics
Above 3.5	Virtually unprocessable
3.0 to 3.5	Processable with difficulty
2.5 to 3.0	Normal processability
2.0 to 2.5	Very easily processable
Below 2.0	Settling difficulties may occur

Aluminum/Liquid-Hydrogen-Slurry-Injected Solid Rocket Booster

The third quasi-hybrid rocket concept analyzed was an aluminum/liquid-hydrogen-slurry-injected solid rocket booster. Rather than changing solids composition to increase the aluminum content in the system, aluminum is added in slurry or gelled form with the liquid hydrogen. The aluminum could be suspended in the liquid hydrogen in fine particulate form as a colloidal suspension. In this way the bulk density of the augmenting fluid can be increased to conserve on tankage volume, and additional aluminum is supplied to the combustion process to optimize specific impulse. In addition, gelation of the aluminum in the liquid hydrogen could improve storage and handling, increase safety, and reduce evaporation of the cryogenic liquid propellant.

The results of thermochemical calculations conducted for the aluminum/liquid-hydrogen-slurry-injected solid rocket booster are shown in figure 13. Peak theoretical specific impulse of 325.9 sec occurs when 45 wt % of the total propellant is aluminum/liquid hydrogen slurry and 50 wt % of the slurry is aluminum. Therefore, aluminum/liquid hydrogen slurry addition can increase the specific impulse of PBAN solid propellant by 74.2 sec. Aluminum/liquid-hydrogen-slurry mass-flow rates and tankage volumes for augmentation of a SRB-size booster are presented in figures 14 and 15, respectively. Figure 16 shows the thrust increase resulting from slurry addition to the solid rocket booster. For large Earth-to-orbit boosters, tankage volumes become excessive with minimum slurry augmentation, regardless of the slight increase in bulk density.

Addition of aluminum metal to liquid hydrogen was considered in this analysis as a means of increasing the aluminum content in the combustion process of the quasi-hybrid rocket to optimize specific impulse. The metal addition also increases the bulk propellant density of the liquid hydrogen, thereby reducing tankage volume and structural mass. However, the concept of metallized propellant systems is not new to rocket propulsion. Metallized propellant systems were first investigated in the early 1960's after the potential advantages of increased propellant density, increased specific impulse, improved storage and handling, reduced evaporation, and improved safety compared to conventional liquid propellants were realized. However, significant efforts in the 1960's failed to resolve the many challenging technological problems associated with metallized propellant systems, and the concept was eventually abandoned as budgets for high-risk/high-payoff propulsion technology began to diminish. A recent evaluation of metallized propellants considering current technology and applications is contained in reference 10.

The use of gel or slurry hydrogen is conceptually attractive for improving specific impulse and bulk propellant density of quasi-hybrid rocket systems, but the many technical challenges associated with metallized propellant systems still exist today. A reliable means to store, transport, and inject the metallized slurry or gel into the combustion chamber must first be developed. Particularly with slurries, the aluminum particles may settle out of the liquid hydrogen during storage or under high gravitational loads imposed by a particular mission. Gels exhibit good storage stability but are more difficult to transport since they are semisolid. Significant gel quantities may also be wasted because of residual deposits in tanks and propellant lines. The result of these slurry and gel storage problems could be a loss in vehicle performance and potential safety hazards. Abrasion and clogging would be a potential problem in the pipes, valves, and turbomachinery for the metal transport system. In addition a reliable metallized propellant injection system would be needed to ensure efficient mixing in the combustion chamber and prevent erosive burning of the solid propellant. The presence of additional metal in the combustion process alone will stimulate the burning rate of the solid propellant. Finally, the aluminum particles in the slurry or gel hydrogen must be extremely small and residence times in the combustion chamber large to minimize combustion inefficiencies and reduce two-phase flow losses. The impact of such performance losses have already been discussed. The aluminum/liquid-hydrogen-slurry-injected solid rocket booster is a novel approach to optimizing the performance of the quasi-hybrid system, but an advanced technology is required to make it practical and safe.

Discussion

The intent of this study was to assess the feasibility of quasi-hybrid rockets for advanced Earth-to-orbit vehicles. A necessary first step in evaluating any advanced propulsion concept is to conduct thermochemical performance calculations. The performance calculations have shown that quasi-hybrid rockets theoretically offer large improvements in specific impulse relative to solid propellant rockets when hydrogen is used as the augmenting fluid. The next step in evaluating an advanced propulsion concept is to determine any potential benefits derived from using the propulsion system in a particular vehicle application. In this process, physical constraints resulting from the requirements of the application must be considered. Calculations were conducted to determine liquid hydrogen tankage volumes required when using quasi-hybrid rockets for STS booster applications. These calculations showed that in actual application improvements in specific impulse are limited by constraints on vehicle size and mass due to the low density of liquid hydrogen. Specific impulse of a quasi-hybrid rocket increases with hydrogen addition, but so does the structural mass of the vehicle because of increases in (hydrogen) tankage volume. Mission analysis to determine any improvements in vehicle performance resulting from the use of quasi-hybrid boosters for an advanced STS booster was beyond the scope of this analysis. However, calculation of hydrogen requirements for such an advanced booster clearly illustrates that hydrogen additions are limited to only a few weight percent, and the advantages stemming from the peak theoretical specific impulse offered by the quasi-hybrid systems could not be practically realized.

Finally, in evaluating advanced propulsion concepts, the potential benefits in vehicle performance must be weighed against safety, cost, and technical considerations. Safety is a major reason why hybrid rockets are currently being considered for an advanced STS booster. Some types of hybrid rockets offer start-stop-restart capability which can potentially make them safer than the current STS solid rocket boosters. The quasi-hybrid rocket is the first logical system to be considered for an advanced STS booster because of the applicability of existing STS hardware. The current space shuttle SRB's could be made quasi-hybrid by hydrogen augmentation, drawing on the existing supply of hydrogen in the external tank. Changing the metal content in the solid propellant grain or adding a slurry of aluminum and liquid hydrogen could further increase performance with additional STS hardware modifications. The specific impulse advantages of such systems have already been discussed. However, the implications of such modifications on safety must be considered. It also remains to be determined whether quasi-hybrid rockets possess the safety advantage of start-stop-restart capability which is desired for the next generation STS boosters.

Critical technologies must also be considered in assessing propulsion concepts for advanced applications. The quasi-hybrid rocket combines many properties, characteristics, and technologies of solid propellant and liquid propellant rockets. However, the application of solid and liquid propellant technologies to hybrid systems remains virtually unexplored. There are also technologies that are unique to quasi-hybrid rocket systems which have never been investigated. Table V compares various structural components of solid propellant, liquid propellant, and quasi-hybrid rockets. The individual structural components of the quasi-hybrid rocket differ only slightly from those of either solid or liquid propellant rockets. The configuration, internal ballistic behavior, and mixing device would be unique to quasi-hybrid systems. Table VI lists some of the properties that characterize quasi-hybrid rockets and compares them with solid propellant and liquid propellant engines. The quasi-hybrid systems offer improved propellant density, a simpler design with only half the valves and regulating devices (hence lower cost), and potentially improved stability characteristics compared to liquid propellant rockets. Compared with solid propellant rockets, quasi-hybrid rockets offer advantages including improved specific impulse, the possibility for thrust vector control, a wider range of possible solid propellant regression rates, and some chance for combustion termination.

However, the quasi-hybrid systems also have unique disadvantages. For example, internal ballistic behavior (calibration and operating point constancy) and combustion efficiency currently represent problems with quasi-hybrid systems. It is important to realize that potential benefits derived

TABLE V.—COMPARISON OF STRUCTURAL COMPONENTS OF CHEMICAL ROCKET ENGINES

Engine component	Solid propellant rocket	Quasi-hybrid rocket	Liquid propellent rocket
Nozzle design	Identical	Identical	Identical
Nozzle/thrust chamber cooling:			
Heat-sink, ablative	Identical	Identical	Identical
Regenerative		Identical	Identical
Combustion chamber	Identical	Identical	
Solid propellant grain:			
Composition	Identical	Identical	
Configuration		(a)	
Internal ballistics		(a)	
Liquid injector		Similar	Similar
Mixing device		(a)	
Ignition system	Identical	Identical	
Liquid feed system		Identical	Identical
Valves/control system		Identical	Identical

[a]Specific to quasi-hybrid rocket.

TABLE VI.—PROPERTIES OF QUASI-HYBRID ROCKETS AS COMPARED WITH SOLID PROPELLANT AND LIQUID PROPELLANT ROCKETS

Property	Better than solid propellant rocket	No advantage or problem area	Better than liquid propellant rocket
Specific impulse	Yes		
Propellant density			Yes
Safety		No advantage	
Simplicity			Yes
Storage stability		No advantage	
Reliability		No advantage	
Cost			Yes
Ignition		No advantage	
Combustion efficiency		Problem	
Combustion stability			Yes
Regression rate range	Yes		
Temperature independency		No advantage	
Calibration		(a)	
Operating point constancy		(a)	
Thrust control	Yes		
Termination/reignition	Yes		

[a]Could represent a problem depending upon engine configuration.

from an advanced propulsion system are inconsequential if the propulsion system cannot satisfy the safety requirements of a particular application, cost for development or operation is unrealistically large, or if required technology cannot be developed. In this respect, safety, cost, and technology issues become more important than performance in assessing the feasibility of advanced propulsion systems for future applications. The discussion that follows is an evaluation of safety and technology areas relevant to quasi-hybrid rockets with emphasis on the use of such systems for advanced Earth-to-orbit booster applications.

Specific Impulse and Propellant Density

Both specific impulse and propellant density must be optimized when selecting a propellant for a particular application. Quasi-hybrid rockets offer a range of specific impulse and bulk propellant density intermediate between solid and liquid propellant rockets. The specific impulse and propellant density for a particular application can be optimized by a suitable choice of solid and liquid propellants. However, quasi-hybrid rocket systems offer less flexibility in this respect than conventional hybrid rocket systems. This is because the choice of liquid propellants for quasi-hybrid systems is limited to those yielding improved thermochemical performance as compared with the solid propellant being used and those satisfying the requirements of the application. Hydrogen proved to be the only suitable choice of augmenting fluid for an advanced quasi-hybrid STS booster.

Safety Considerations

Safety is a primary consideration when evaluating any propulsion concept for a given application. An advanced propulsion system should not be considered a viable candidate if it cannot satisfy the safety requirements of the application, regardless of any performance advantages offered by the system. The quasi-hybrid rocket offers improved specific impulse compared to PBAN solid rocket boosters. However, the practicality of such systems for near-term Earth-to-orbit applications remains to be judged based on criteria other than performance.

The potential safety advantage of start-stop-restart capability is an important reason why hybrid rocket systems are currently being considered for advanced STS booster applications. In conventional hybrid rockets the solid and liquid propellants are in different physical states and are separately stored. Combustion termination is ensured by stopping the flow of liquid oxidizer to the solid fuel of the hybrid rocket. The rocket can be restarted by reinitiating the flow of liquid oxidizer and reigniting the propellants. In addition, since the solid propellant is entirely fuel (or oxidizer in the case of reverse hybrid rockets), cracks in the propellant grain can not generally endanger the engine as they would with all-solid propellant motors (ref. 1). Therefore, conventional hybrid rockets are relatively safe with respect to explosion and accidental detonation and can be regulated, making them potential candidates for advanced Earth-to-orbit boosters.

However, these safety advantages over solid propellant rockets possessed by conventional hybrid rocket systems are not inherent with quasi-hybrid rockets. The reason for this is that the solid propellant in quasi-hybrid rockets contains both fuel and oxidizer. Just as with solid propellant rockets, quasi-hybrid rockets must be protected at all times from harsh environments which may subject them to shock or vibration, thereby causing premature ignition and uncontrolled combustion. Cracks in the solid propellant grain of quasi-hybrid rockets can result in erosive burning and endanger life just as with solid propellant rockets. Quasi-hybrid rockets can also have unique operational hazards not found with all-liquid or all-solid propellant rocket systems. For instance, head-end injection of the augmenting fluid into the solid propellant combustion chamber could create an uncontrollable localized solid burning and chamber pressure rise that would result in catastrophic failure. Inefficient mixing of the augmenting fluid, resulting in a fuel-rich flooded chamber, could also lead to catastrophic failure. Technology must be developed to control these and other critical operation problems in order to use quasi-hybrid rockets in practical application.

A final major limitation of quasi-hybrid rockets when considering them for manned booster applications is lack of reliable start-stop-restart capability. Combustion termination is not insured with quasi-hybrid systems by regulation of the liquid propellant because the solid propellant can burn independently of the liquid injection. The possibility of combustion termination and reignition of a quasi-hybrid rocket by regulation of the liquid propellant injection was investigated as part of this study. The results of this investigation, indicate that quasi-hybrid rockets have no practical safety advantage for start-stop-restart capability in advanced STS booster applications. (See the section Solid Propellant Combustion Termination and Reignition.) Therefore, although the specific impulse of quasi-hybrid rockets looks very promising compared with that of conventional solid propellant rockets, there are no apparent safety advantages. In fact the quasi-hybrid rocket concept may have some unique operational safety problems. Safety considerations would indicate that conventional hybrid (or reverse hybrid) rockets are a better choice than quasi-hybrid rockets to consider for advanced Earth-to-orbit boosters.

Liquid Injection

The injection of liquid into a quasi-hybrid rocket may be accomplished by two methods as illustrated in figure 17. The first method, head-end injection into the combustion chamber, represents the typical injection mode of conventional hybrid rockets. The augmenting fluid is injected directly into the core region of the solid propellant and participates in the combustion process. This method would be required for an aluminum/liquid-hydrogen-slurry-injected quasi-hybrid rocket because the aluminum in the slurry must become involved in the combustion process. Efficient combustion of the aluminum to increase delivered specific impulse is realized only through a long residence time within the combustion chamber. Therefore, only small fluid additions can be practically used with head-end injection to ensure thorough combustion and to avoid potential crack development caused by cryogenic cooling of the solid propellant to its glass point.

The second injection method involves the circumferential injection of the augmenting fluid into a motor-cased reaction chamber downstream of the solid propellant. Augmentation by aft-end injection provides the possible advantages of thrust vector control (TVC), and throat cooling. Either injection method is applicable to liquid hydrogen augmentation of solid rocket boosters. However, with aft-end injection, regression rate of the solid propellant would be more controlled, and safety concerns associated with injection of the liquid into the solid propellant core would be eliminated.

In calculating liquid mass flow rates, tankage volumes, and thrust levels in the analysis of this report, an assumption was made that the solids mass flow rate (burning rate) remained constant with liquid augmentation. This assumption is good for the quasi-hybrid concepts with pure liquid (hydrogen) injection since aft-end injection could be assumed. However, for the quasi-hybrid concept with aluminum/liquid hydrogen injection, head-end injection would be required. In this case the assumption of constant solids burning rate can be satisfied by assuming a change in engine configuration (burning area and web thickness of the solid propellant in the booster) between the quasi-hybrid system and the all-solid system.

Ignition and Combustion Properties

Ignition and combustion in quasi-hybrid rockets are complex transient thermochemical processes. Ignition in quasi-hybrid systems occurs similarly as in conventional solid propellant rockets. Ignition methods suitable for solid propellant rockets (such as pyrotechnic ignition) would also be applicable to ignition of quasi-hybrid rockets. The start-up phase of a quasi-hybrid engine, which represents the transition phase between solid propellant ignition and the attainment of steady-state operation, can be envisioned to occur in several steps. Ignition of the solid propellant is followed by a pressure buildup in the combustion and reaction chambers until a quasi-steady operating point is attained. The liquid propellant valve is opened, and liquid is injected into the combustion or reaction chamber. Chamber pressure rises as the liquid propellant vaporizes and burns until the steady-state operating point is achieved.

Combustion processes in quasi-hybrid systems are highly dependent on the configuration of the rocket and can exhibit characteristics of both a conventional hybrid rocket and a solid propellant rocket. The method of liquid injection mainly influences which characteristics are dominant. Head-end or aft-end liquid injection can be used. In either case the injection system is composed of hardware conforming more or less to the methods used with liquid rocket propellants. Quasi-hybrid systems with aft-end liquid injection exhibit combustion characteristics of solid propellant rockets. In quasi-hybrid systems hydrogen ideally acts strictly as a low-molecular-weight working fluid which converts the combustion energy to thrust. Aft-end injection of hydrogen is more practical than head-end injection as long as energy exchange occurs efficiently in the reaction chamber.

The combustion processes in quasi-hybrid rockets with head-end injection are more complex than those associated with aft-end injection. Little is known about combustion phenomena in quasi-hybrid rockets with head-end injection, but one might expect the combustion processes to exhibit characteristics similar to conventional hybrid rockets if significant quantities of augmenting fluid are involved.

Combustion in a hybrid rocket is quite different from that in a solid propellant rocket. The augmenting fluid, after having been turned into a mixture of droplets and gasified liquid as a result of its passage through the injector, streams through the combustion channel during the operating phase of the engine. The solid propellant is partly decomposed and evaporated (gasified) at the solid surface by convective (or convective plus radiative) heat transfer and diffuses inward toward the center of the combustion chamber. A boundary layer is formed above the surface of the solid propellant, and this layer is fed radially by the liquid entering from the central core and by gasified solid propellant. In the boundary layer the concentration of the augmenting fluid diminishes as one moves toward the surface of the solid. Likewise, the concentration of the solid propellant gases diminishes in the parts of the boundary layer farther removed from the surface of the solid. Figure 18 is a schematic representation of the combustion process. The boundary layer is subdivided into three stages of combustion. When the augmenting fluid is a liquid, the droplets pass right through the boundary layer and come into direct contact with the evaporated solid propellant to form a premixed reaction zone. Since the droplets become heated as they pass through the boundary layer and tend to evaporate, a diffusion flame zone is formed above the premixed reaction zone. At a point where the ratio of oxidizer-to-fuel concentration (O/F ratio) is on the fuel-rich side of stoichiometric, combustion occurs in a layer whose thickness is of the order of 10 percent of the boundary layer thickness. The rate of combustion is limited by the rate at which heat is transferred from the flame to the solid surface rather than by the chemical kinetics of the flame, except at very low pressures. Thus, the rate of combustion is limited by fluid dynamic processes rather than chemical kinetics, as is the case for classical solid propellants. The zone above the diffusion flame zone is a flow of gaseous hydrogen and other combustion gases. Given the continuous influx of material, the boundary layer is almost always turbulent. The thickness of the boundary layer tends to increase in the downstream direction, and in the case of a hollow cylinder it will fill the entire channel cross section after about 5 diameters. After about 25 diameters, further combustion of the augmenting fluid is not achieved (refs. 1, 2, and 9). At this point, the unburned augmenting fluid simply acts to increase mass flow, exchange heat with the combustion products, and to further lower the average molecular weight of the exhaust products.

Quasi-hybrid rockets would be expected to exhibit combustion stability characteristics similar to solid propellant rockets. The combustion chamber of a solid rocket is acoustically softer than that of a liquid rocket. Acoustical damping occurs due to particulate damping by the solids present, among other things. It is interesting to note that aluminum addition therefore favorably influences combustion stability, and those systems with high metal loadings would be expected to exhibit the greatest stability (but the lowest combustion efficiency). The use of powdered metal fuel in solid propellants is credited with reducing, if not eliminating, problems of severe transverse oscillations in solid propellant rockets. For example, the addition of 2 to 5 wt % aluminum powder to a nonmetallized propellant has been effective in damping high-frequency (transverse) oscillations (ref. 2).

Finally, quasi-hybrid rockets, like conventional hybrid rockets, may exhibit a problem with low combustion efficiency because of the layered and multiphase structure of the flow in the combustion and reaction chambers. This is particularly true with quasi-hybrid systems which use head-end liquid injection. Mixing devices internal to the combustion chamber could be employed in an effort to improve the combustion efficiency. However, the technology to use such devices is currently undeveloped. Combustion efficiency is one factor that adversely influences performance and, hence, decreases the theoretical specific impulse values reported here. Experimental testing would be required to further explore this technology area and to study the combustion phenomena in quasi-hybrid rockets.

Internal Ballistic Behavior

Internal ballistic properties are those parameters that govern the burning rate and mass discharge rate of the rocket. They include the sensitivity of the burning rate of the propellant to factors such as propellant composition, grain temperature, chamber pressure, and gas velocity. Burning (regression or ablation) rate is the most important parameter when considering internal ballistic behavior, because it determines both the burning surface required for a given mass flow rate and the web thickness (i.e., the minimum thickness of the solid from the initial burning surface to the surface of the insulated liner of the casing) required for a given thrust duration. Burning rate for solid propellant rockets is a strong function of chamber pressure. The relationship between burning rate and chamber pressure is typically expressed as

$$\dot{r} = a(P_c)^n$$

where $\dot{r}$ is the burning rate in inches per second, P_c is the chamber pressure in pounds per square inch, a is an empirical constant influenced by ambient grain temperature, and n is the burning rate pressure exponent (empirically determined) which describes the influence of chamber pressure on burning rate. For the space shuttle solid rocket boosters, which use PBAN solid propellant, the empirical constants have been determined to be $a = 0.053344$ and $n = 0.30$, corresponding to a burning rate of 0.366 in./sec at 614 psi. In addition to the strong influences of the solid propellant composition and geometry, temperature plays an important role. Combustion gas temperature affects chemical reactions, and the initial ambient temperature of the propellant grain prior to combustion influences burning rate. Quasi-hybrid rockets would be expected to have the same temperature dependency on burning rate as solid propellant rockets. Finally, combustion gas velocity and motor acceleration affect solid propellant burning rate. These factors tend to increase propellant burning rate after ignition and may lead to hazardous erosive (or localized) burning in the aft segments of the booster.

Clearly, quasi-hybrid rockets with aft-end liquid injection will exhibit internal ballistic characteristics of solid propellant rockets. However, the internal ballistic behavior of quasi-hybrid rockets with head-end liquid injection is difficult to determine because of lack of research in this area. One might expect the internal ballistic behavior to be similar to that of a conventional hybrid rocket if significant quantities of fluid injection are involved. In conventional hybrid and quasi-hybrid rockets with head-end injection, the liquid mass flow rate and configuration of the rocket will have the strongest influences on the internal ballistic behavior. The burning rate of a conventional hybrid rocket has many parameters but is primarily a function of pressure, temperature of the propellant grain, grain composition and configuration, liquid mass flow rate, and the liquid injection system. The prediction of burning rate and the avoidance of localized high burning rates (erosive burning), which can result in burn-through areas or excessive solid propellant slivers (propellant remaining or expelled through the nozzle at the time of web burnout), is very difficult with hybrid rockets (ref. 2). For this reason the calibration (exact prediction of burnout with no residual propellant components remaining) and ability to maintain operating point constancy (constant solids regression rate) would be a problem with quasi-hybrid systems that use head-end injection.

The most important parameter governing the regression rate in hybrid systems is the mass flux per unit area, G (which is defined as the ratio between the mass flow rate $\dot{m}$ and the free cross-sectional area A of the channel). In hybrid engines the mass flux per unit area plays much the same role as the combustion chamber pressure in solid propellant rockets. It represents the dominant factor in the description of the burning rate. Since propellant continually joins the flow along the channel axis of the combustion chamber, the mass flow rate increases as one moves downstream and G will assume different local values. A linear relationship exists for limited areas if one plots the burning rate against the mass flux per unit area on logarithmic paper. The following empirical law describing the relationship between the burning rate and G applies

$$\dot{r} = kG^{\alpha}$$

where k and α are experimentally determined constants. The burning rates of conventional hybrid rockets are characteristically about an order of magnitude smaller than typical all-solid propellant burning rates (ref. 9). Liquid injection also allows for a greater range of regression rates with any type of hybrid system than with all-solid propellant rockets.

Solid Propellant Combustion Termination and Reignition

A solid rocket booster in which combustion could be safely terminated would be safer than the current STS boosters and would allow for shuttle abort during operation. A primary advantage of conventional hybrid rockets is that combustion termination can be ensured at any time during engine operation. Conventional hybrid rockets have start-stop-restart capability because the solid propellant is entirely fuel. The liquid injection supplies the oxidizer, and termination of the liquid injection terminates combustion. Reignition commences when the liquid oxidizer is again introduced into the rocket. Combustion termination and reignition in reverse hybrid rockets is similar since the physical states of the fuel and oxidizer are simply reversed. However, combustion termination is not ensured with quasi-hybrid rockets because the solid propellant contains both oxidizer and fuel, and combustion can occur independently of the liquid injection.

Only in a quasi-hybrid rocket with head-end liquid injection might it be possible to terminate combustion during booster operation. Two scenarios can be envisioned. During nominal operation of the quasi-hybrid rocket, rapid depressurization might be accomplished by decreasing or stopping the liquid injection (safety blowout plugs are commonly employed in solid propellant rockets for combustion termination by rapid depressurization). Vehicle considerations limit the liquid injections in large Earth-to-orbit boosters to relatively small quantities, and the possibility of combustion termination by stopping the liquid injection seems remote. The other possibility is to increase the liquid injection in an effort to quench the combustion flame. Head-end liquid injection would be required to extinguish by this method. The internal ballistic problems associated with head-end injection have already been discussed. The safety hazards associated with expulsion of large unburned quantities of liquid hydrogen into the atmosphere also severely limit the practicality of this extinguishment method. However, both possibilities were investigated further in connection with hydrogen augmentation of PBAN solid propellant rockets.

Since early 1963, the injection of fluid into a solid propellant rocket motor to effect combustion termination has been investigated. Fluid extinguishment was considered in connection with mission abort systems for on-the-pad thrust termination of large solid propellant boosters (ref. 11). The focus of this investigation is on the combustion extinguishment of a PBAN solid propellant rocket by liquid hydrogen injection. Previous experience with fluid extinguishment has illustrated liquid water injection (hydroquenching), and liquid carbon dioxide (CO_2) injection as a viable means of combustion termination of a PBAN solid propellant (refs. 11 and 12). However, liquid hydrogen injection for combustion extinguishment has not yet been demonstrated.

Fluid extinguishment of a solid propellant rocket motor.— The extinguishment of a solid propellant motor by fluid injection is a complex transient process dependent on numerous physical and chemical factors. With head-end fluid injection, the longitudinal distribution of fluid plays an important role in the transient pressure history and surface extinguishment of the motor during combustion termination. The rate of surface extinguishment is dependent on penetration of the liquid to the surface with adequate momentum to effect quenching of the flame. Combustion termination occurs progressively down the grain surface rather than as a persistent effect on the overall surface. The largest injectant requirement stems from the need to cool the motor hardware to prevent reignition, hence, motor geometry is a relevant factor in fluid injection extinguishment. Different length motors of the same diameter have similar critical extinguishment limits (based on hydroquenching), but the longer motors are driven to a lower pressure during similar injection times. Motors with large diameters require a higher flow rate ratio, $\dot{w}_l/\dot{w}_p$ (fluid flow rate/propellant flow rate), at any certain w_l/A_b (total fluid injected/area of burning) than motors with smaller diameters. The latter represents a higher injectant efficiency because shorter fluid trajectories are needed to reach the burning surface (ref. 11).

In actual static tests, the space shuttle solid rocket booster incorporated a post-fire carbon dioxide (CO_2) quench system. Liquid CO_2 was injected through the igniter at the head-end and through a probe which was moved around on tracks into the nozzle (aft-end) after SRB burnout. Extinguishment occurred as described above. As a reference point to this investigation, the total CO_2 mass expelled for extinguishment was 20 884 kg (46 000 lb) for 350 sec. The total flow was calculated as that required to cool the nozzle and all internal motor materials below their pyrolysis temperature (ref. 12). In actual mission abort applications, the quenching fluid injection time would be dramatically less than 350 sec. In turn, the total injected fluid mass (and volume flow rate) required to extinguish the solid propellant and prevent reignition would increase beyond 20 884 kg (46 000 lb). Additionally, because of its reactivity, low density, and low heat of vaporization, liquid hydrogen is less effective as an extinguishing fluid than carbon dioxide. There are also major safety problems associated with extinguishment by this method in practical applications because of the possible expulsion of large unburned quantities of hydrogen into the atmosphere. It is clear that combustion termination in quasi-hybrid rockets by liquid hydrogen extinguishment is not a practical advantage.

Rapid depressurization. – The alternative to termination by fluid extinguishment is rapid depressurization. Combustion extinguishment by rapid depressurization may be accomplished by simply decreasing or stopping the influx of liquid hydrogen into the booster chamber. Combustion extinguishment occurs when there is sufficient heat loss within the solid propellant rocket booster system, created by a rapid pressure decay, that the burning rate approaches a zero steady-state level. The depressurization rate, final chamber pressure after depressurization, and amount of heat loss associated with the pressure decay determine whether extinguishment occurs. If the final chamber pressure is below the deflagration pressure of the propellant (the lowest possible pressure for steady-state burning) then combustion will be extinguished. For a final pressure that settles above the deflagration limit, two stable physical states are feasible. If there is insufficient heat loss, the solid propellant will continue to burn at a lower steady-state burning rate at the reduced pressure level. However, if the depressurization rate is fast enough to expel sufficient heat, burning will approach zero and combustion will be terminated (ref. 13). The combustion process is quite sensitive to pressure decreases, and momentary combustion extinguishment has been observed at pressure decay rates nearly an order of magnitude lower than required to extinguish combustion permanently. Energy for reignition after momentary extinguishment results from a combination of residual heat in the propellant surface and the chamber gases. It has been observed that once combustion has been extinguished by a rapid pressure decrease, the propellant will not subsequently reignite in a low ambient pressure environment (refs. 14 and 15). Considering that the deflagration pressure of PBAN is less than atmospheric pressure and that liquid hydrogen augmentations are limited to relatively small quantities in practical application, the possibility of combustion termination by rapid depressurization seems remote. The quasi-hybrid rocket offers no clear advantage over the solid propellant rocket for start-stop-restart capability in Earth-to-orbit booster applications.

Alternate extinguishment methods. – Alternate extinguishment methods are available for combustion termination of rocket systems which use solid propellants. Extinguishment of the burning propellants can be initiated by using a chain charge (pyrocapsule) of an active explosive material with a regular speed of detonation to burst a compressed coolant upon the solid surface. The detonation force has to be calculated so that it supplies enough energy to the coolant particles to reach the burning surface, but is not destructive to hardware. The fast injection of a dust coolant (e.g., ammonium bicarbonate) into a combustion chamber forms a layer of subliming crystals over the surface of the fuel. Extinguishing with a pyrocapsule has several advantages. The combustion stopping system is compact and has a simple construction. There are no moving parts in it so it is relatively stable with respect to inertial forces (ref. 16). However, combustion can not be reinitiated after termination with a pyrocapsule.

Concluding Remarks

The purpose of this study was to evaluate the potential of quasi-hybrid rockets for advanced Earth-to-orbit booster applications. Specific emphasis was placed on assessing the practicality of quasi-hybrid rockets as replacements for the space shuttle SRB's. Hybrid booster systems are currently under consideration for advanced Earth-to-orbit boosters mainly because they offer higher performance than solid propellant rockets and have a potential safety advantage of start-stop-restart capability. The quasi-hybrid rocket, which is one type of hybrid rocket, is the first logical hybrid system to be evaluated for such application because of the applicability of existing space shuttle STS hardware. The space shuttle SRB's could conceivably be made quasi-hybrid by hydrogen augmentation, drawing on the existing supply of hydrogen in the external tank.

Thermochemical performance calculations were first conducted to predict the specific impulse advantages of quasi-hybrid rockets compared to PBAN solid propellant rockets. The performance calculations showed large improvements in specific impulse relative to PBAN solid propellant rockets when hydrogen is used as the augmenting fluid. Addition of extra aluminum to the combustion process by aluminum/liquid-hydrogen-slurry addition or by increasing the metal content in the PBAN solid propellant can further improve theoretical performance. Calculations were then conducted to determine propellant requirements for a nominal mission by using the quasi-hybrid systems for Earth-to-orbit booster applications. Liquid hydrogen additions are limited to only a few weight percent before hydrogen tankage requirements become excessive. Therefore, the advantages stemming from the peak theoretical specific impulse offered by the quasi-hybrid systems could not be practically realized in advanced STS booster applications.

Finally, the feasibility of quasi-hybrid rockets for near-term Earth-to-orbit booster applications was evaluated based on operational and safety considerations. Quasi-hybrid rockets do offer some potential advantages over liquid propellant and solid propellant propulsion systems. Relative to liquid propellant rockets, quasi-hybrid systems offer design simplicity, lower cost, improved propellant density, and potentially improved stability characteristics. Advantages relative to solid propellant rockets include improved specific impulse, the possibility for thrust vector control, and a wider range of possible solid propellant regression rates.

However, quasi-hybrid rockets have some unique disadvantages. The conclusion reached from a complete review of relevant safety and technology areas was that quasi-hybrid rockets are an inappropriate choice for near-term Earth-to-orbit booster applications. One reason is that quasi-hybrid rockets offer no apparent safety advantage for start-stop-restart capability, which is a primary requirement for an advanced STS booster. In fact quasi-hybrid systems possess some severe operational safety hazards. Quasi-hybrid systems also have internal ballistic problems in the areas of calibration, operating point constancy, and combustion efficiency.

As a recommendation for future study, a conventional hybrid rocket has more potential for an advanced Earth-to-orbit booster than a quasi-hybrid rocket. This type of hybrid rocket has reliable start-stop-restart capability and offers higher performance than conventional solid propellant rockets. In addition, conventional hybrid rockets use the much denser liquid oxidizer as the augmenting fluid rather than low density liquid hydrogen. Future efforts in the hybrid rocket area for advanced Earth-to-orbit booster systems with start-stop-restart capability and higher performance than solid propellant rocket boosters should focus on conventional hybrid rockets.

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Cleveland, Ohio, May 12, 1987

Appendix A

Complex Equilibrium Composition for Quasi-Hybrid Rocket Boosters

TABLE A-I.—COMPLEX EQUILIBRIUM COMPOSITION DATA FOR LIQUID-HYDROGEN-INJECTED SOLID ROCKET BOOSTER

Liquid hydrogen, wt %	Ammonium perchlorate, wt %	Aluminum, wt %	Binder, wt %	Curing agent, wt %	Burning rate catalyst, wt %	Specific impulse, I_{sp}, sec
0	69.840	16.00	12.040	1.960	0.160	251.7
5	66.348	15.20	11.438	1.862	.152	276.5
10	62.856	14.40	10.836	1.764	.144	280.4
15	59.364	13.60	10.234	1.666	.136	283.5
20	55.872	12.80	9.632	1.568	.128	291.8
25	52.380	12.00	9.030	1.470	.120	293.8
30	48.888	11.20	8.428	1.372	.112	286.8
35	45.396	10.40	7.826	1.274	.104	281.8
40	41.904	9.60	7.224	1.176	.096	278.2
45	38.412	8.80	6.622	1.078	.088	270.1
50	34.920	8.00	6.020	.980	.080	262.1

TABLE A-II.—COMPLEX EQUILIBRIUM COMPOSITION DATA FOR LIQUID-HYDROGEN-INJECTED SOLID ROCKET BOOSTER WITH A SOLIDS COMPOSITION CHANGE

Liquid hydrogen, wt %	Ammonium perchlorate, wt %	Aluminum, wt %	Binder,[a] wt %	Curing agent,[b] wt %	Burning rate catalyst,[c] wt %	Specific impulse, I_{sp}, sec
0	73.840	12.00	12.040	1.960	0.160	251.5
5	70.148	11.40	11.438	1.862	.152	272.0
10	66.456	10.80	10.836	1.764	.144	273.3
15	62.764	10.20	10.234	1.666	.136	277.5
20	59.072	9.60	9.632	1.568	.128	286.7
25	55.380	9.00	9.030	1.470	.120	286.9
30	51.688	8.40	8.428	1.372	.112	280.3
0	69.840	16.00	12.040	1.960	0.160	251.7
5	66.348	15.20	11.438	1.862	.152	276.5
10	62.856	14.40	10.836	1.764	.144	280.4
15	59.364	13.60	10.234	1.666	.136	283.5
20	55.872	12.80	9.632	1.568	.128	291.8
25	52.380	12.00	9.030	1.470	.120	293.8
30	48.888	11.20	8.428	1.372	.112	286.8
0	65.840	20.00	12.040	1.960	0.160	252.6
5	62.548	19.00	11.438	1.862	.152	281.1
10	59.256	18.00	10.836	1.764	.144	287.3
15	55.964	17.00	10.234	1.666	.136	289.8
20	52.672	16.00	9.632	1.568	.128	296.8
25	49.380	15.00	9.030	1.470	.120	299.9
30	46.088	14.00	8.428	1.372	.112	293.4

[a]Constant 12.040 wt %.
[b]Constant 1.960 wt %.
[c]Constant 0.160 wt %.

TABLE A-II.—Concluded.

Liquid hydrogen, wt %	Ammonium perchlorate, wt %	Aluminum, wt %	Binder,[a] wt %	Curing agent,[b] wt %	Burning rate catalyst,[c] wt %	Specific impulse, I_{sp}, sec
0	61.840	24.00	12.040	1.960	0.160	250.3
5	58.748	22.80	11.438	1.862	.152	280.3
10	55.656	21.60	10.836	1.764	.144	294.3
15	52.564	20.40	10.234	1.666	.136	297.3
10	49.472	19.20	9.632	1.568	.128	302.4
25	46.380	18.00	9.030	1.470	.120	305.8
30	43.288	16.80	8.428	1.372	.112	300.0
0	57.840	28.00	12.040	1.960	0.160	242.0
5	54.948	26.60	11.438	1.862	.152	272.4
10	52.056	25.20	10.836	1.764	.144	299.3
15	49.164	23.80	10.234	1.666	.136	307.0
20	46.272	22.40	9.632	1.568	.128	309.8
25	43.380	21.00	9.030	1.470	.120	311.8
30	40.488	19.60	8.428	1.372	.112	306.6
0	53.840	32.00	12.040	1.960	0.160	231.3
5	51.148	30.40	11.438	1.862	.152	268.6
10	48.456	28.80	10.836	1.764	.144	298.9
15	45.764	27.20	10.234	1.666	.136	314.5
20	43.072	25.60	9.632	1.568	.128	318.8
25	40.380	24.00	9.030	1.470	.120	318.7
30	37.688	22.40	8.428	.112	1.372	313.2
0	49.840	36.00	12.040	1.960	0.160	223.2
5	47.348	34.20	11.438	1.862	.152	265.0
10	44.856	32.40	10.836	1.764	.144	296.4
15	42.364	30.60	10.234	1.666	.136	315.0
20	39.872	28.80	9.632	1.568	.128	320.8
25	37.380	27.00	9.030	1.470	.120	320.9
30	34.888	25.20	8.428	1.372	.112	315.2
0	45.840	40.00	12.040	1.960	0.160	215.1
5	43.548	38.00	11.438	1.862	.152	262.0
10	41.256	36.00	10.836	1.764	.144	294.5
15	38.964	34.00	10.234	1.666	.136	313.9
20	36.672	32.00	9.632[a]	1.568	.128	319.9
25	34.380	30.00	9.030	1.470	.120	320.6
30	32.088	28.00	8.428	1.372	.112	315.3

[a]Constant 12.040 wt %.
[b]Constant 1.960 wt %.
[c]Constant 0.160 wt %.

TABLE A-III.—COMPLEX EQUILIBRIUM COMPOSITION DATA FOR ALUMINUM/ LIQUID-HYDROGEN-SLURRY-INJECTED SOLID ROCKET BOOSTER

Ratio of aluminum/ liquid hydrogen slurry to solids, wt %	Liquid hydrogen, wt %	Ammonium perchlorate,[a] wt %	Aluminum,[b] wt %	Binder,[c] wt %	Curing agent,[d] wt %	Burning rate catalyst,[e] wt %	Specific impulse, I_{sp}, sec
Slurry, 0 wt % aluminum in liquid hydrogen							
0	0	69.840	16.0	12.040	1.960	0.160	251.7
5	5	66.348	15.2	11.438	1.862	.152	276.5
10	10	62.856	14.4	10.836	1.764	.144	280.4
15	15	59.364	13.6	10.234	1.666	.136	283.5
20	20	55.872	12.8	9.632	1.568	.128	291.8
25	25	52.380	12.0	9.030	1.470	.120	293.8
30	30	48.888	11.2	8.428	1.372	.112	286.8
35	35	45.396	10.4	7.826	1.274	.104	281.8
40	40	41.904	9.6	7.224	1.176	.096	278.2
45	45	38.412	8.8	6.622	1.078	.088	270.1
50	50	34.920	8.0	6.020	.980	.080	262.1
Slurry, 10 wt % aluminum in liquid hydrogen							
0	0	69.840	16.0	12.040	1.960	0.160	251.7
5	4.5	66.348	15.7	11.438	1.862	.152	275.9
10	9	62.856	15.4	10.836	1.764	.144	282.3
15	13.5	59.364	15.1	10.234	1.666	.136	284.7
20	18	55.872	14.8	9.632	1.568	.128	291.0
25	22.5	52.380	14.5	9.030	1.470	.120	298.3
30	27	48.888	14.2	8.428	1.372	.112	297.5
35	31.5	45.396	13.9	7.826	1.274	.104	291.9
40	36	41.904	13.6	7.224	1.176	.096	288.3
45	40.5	38.412	13.3	6.622	1.078	.088	285.7
50	45	34.920	13.0	6.020	.980	.080	280.2
Slurry, 20 wt % aluminum in liquid hydrogen							
0	0	69.840	16.0	12.040	1.960	0.160	251.7
5	4	66.348	16.2	11.438	1.862	.152	275.0
10	8	62.856	16.4	10.836	1.764	.144	284.2
15	12	59.364	16.6	10.234	1.666	.136	286.8
20	16	55.872	16.8	9.632	1.568	.128	291.6
25	20	52.380	17.0	9.030	1.470	.120	299.2
30	24	48.888	17.2	8.428	1.372	.112	304.5
35	28	45.396	17.4	7.826	1.274	.104	304.3
40	32	41.904	17.6	7.224	1.176	.096	300.2
45	36	38.412	17.8	6.622	1.078	.088	297.3
50	40	34.920	18.0	6.020	.980	.080	295.9

[a]Constant 69.840 wt %.
[b]Constant in solid propellant 16.0 wt %.
[c]Constant 12.040 wt %.
[d]Constant 1.960 wt %.
[e]Constant 0.160 wt %.

TABLE A-III.—Continued.

Ratio of aluminum/ liquid hydrogen slurry to solids, wt %	Liquid hydrogen, wt %	Ammonium perchlorate,[a] wt %	Aluminum,[b] wt %	Binder,[c] wt %	Curing agent,[d] wt %	Burning rate catalyst,[e] wt %	Specific impulse, I_{sp}, sec
Slurry, 30 wt % aluminum in liquid hydrogen							
0	0	69.840	16.0	12.040	1.960	0.160	251.7
5	3.5	66.348	16.1	11.438	1.862	.152	273.8
10	7	62.856	17.4	10.836	1.764	.144	285.5
15	10.5	59.364	18.1	10.234	1.666	.136	289.3
20	14	55.872	18.8	9.632	1.568	.128	293.6
25	17.5	52.380	19.5	9.030	1.470	.120	299.7
30	21	48.888	20.2	8.428	1.372	.112	307.3
35	24.5	45.396	20.9	7.826	1.274	.104	312.4
40	28	41.904	21.6	7.224	1.176	.096	313.7
45	31.5	38.412	22.3	6.622	1.078	.088	312.0
50	35	34.920	23.0	6.020	.980	.080	308.4
Slurry, 40 wt % aluminum in liquid hydrogen							
0	0	69.840	16.0	12.040	1.960	0.160	251.7
5	3	66.348	17.2	11.438	1.862	.152	272.1
10	6	62.856	18.4	10.836	1.764	.144	283.9
15	9	59.364	19.6	10.234	1.666	.136	291.8
20	12	55.872	20.8	9.632	1.568	.128	296.5
25	15	52.380	22.0	9.030	1.470	.120	303.0
30	18	48.888	23.2	8.428	1.372	.112	310.2
35	21	45.396	24.4	7.826	1.274	.104	317.9
40	24	41.904	25.6	7.224	1.176	.096	323.7
45	27	38.412	26.8	6.622	1.078	.088	322.3
50	30	34.920	28.0	6.020	.980	.080	318.8
Slurry, 50 wt % aluminum in liquid hydrogen							
0	0	69.840	16.0	12.040	1.960	0.160	251.7
5	2.5	66.348	17.7	11.438	1.862	.152	269.9
10	5	62.856	19.4	10.836	1.764	.144	282.4
15	7.5	59.364	21.1	10.234	1.666	.136	292.6
20	10	55.872	22.8	9.632	1.568	.128	298.9
25	12.5	52.380	24.5	9.030	1.470	.120	306.3
30	15	48.888	26.2	8.428	1.372	.112	314.5
35	17.5	45.396	27.9	7.826	1.274	.104	321.9
40	20	41.904	29.6	7.224	1.176	.096	325.2
45	22.5	38.412	31.3	6.622	1.078	.088	325.9
50	25	34.920	33.0	6.020	0.980	.080	324.4

[a]Constant 69.840 wt %.
[b]Constant in solid propellant 16.0 wt %.
[c]Constant 12.040 wt %.
[d]Constant 1.960 wt %.
[e]Constant 0.160 wt %.

TABLE A-III.—Concluded.

Ratio of aluminum/ liquid hydrogen slurry to solids, wt %	Liquid hydrogen, wt %	Ammonium perchlorate,[a] wt %	Aluminum,[b] wt %	Binder,[c] wt %	Curing agent,[d] wt %	Burning rate catalyst,[e] wt %	Specific impulse, I_{sp}, sec
Slurry, 60 wt % aluminum in liquid hydrogen							
0	0	69.840	16.0	12.040	1.960	0.160	251.7
5	2	66.348	18.2	11.438	1.862	.152	267.2
10	4	62.856	20.4	10.836	1.764	.144	279.4
15	6	59.364	22.6	10.234	1.666	.136	289.1
20	8	55.872	24.8	9.632	1.568	.128	295.4
25	10	52.380	27.0	9.030	1.470	.120	301.9
30	12	48.888	29.2	8.428	1.372	.112	309.9
35	14	45.396	31.4	7.826	1.274	.104	316.3
40	16	41.904	33.6	7.224	1.176	.096	320.5
45	18	38.412	35.8	6.622	1.078	.088	322.6
50	20	34.920	38.0	6.020	.980	.080	313.8

[a]Constant 69.840 wt %.
[b]Constant in solid propellant 16.0 wt %.
[c]Constant 12.040 wt %.
[d]Constant 1.960 wt %.
[e]Constant 0.160 wt %.

Appendix B
Calculation of Rocket Parameters

Propellant Flow Rate

The flow rates of the augmenting fluid (denoted below as fluid), liquid hydrogen, or liquid hydrogen/aluminum slurry, were calculated from a ratio of augmenting fluid flow rate $\dot{w}_{\text{fluid}}$ to total flow rate $\dot{w}_{\text{total}}$ (i.e., weight fraction of augmenting fluid) as follows:

$$\frac{\dot{w}_{\text{fluid}}}{\dot{w}_{\text{total}}} = X = \text{weight fraction of augmenting fluid} \tag{1}$$

where

$$\dot{w}_{\text{total}} = \dot{w}_{\text{fluid}} + \dot{w}_{\text{solid}} \tag{2}$$

The fluid flow rate is thus derived from the substitution of equation (2) into equation (1)

$$\dot{w}_{\text{fluid}} = X(\dot{w}_{\text{total}})$$

$$\dot{w}_{\text{fluid}} = X(\dot{w}_{\text{fluid}} + \dot{w}_{\text{solid}})$$

$$(1 - X)\dot{w}_{\text{fluid}} = (X)\dot{w}_{\text{solid}}$$

Thus,

$$\dot{w}_{\text{fluid}} = \frac{X}{1 - X}(\dot{w}_{\text{solid}}) \tag{3}$$

The solids flow rate $\dot{w}_{\text{solid}}$ is derived from the density and velocity (from the CEC program) of the combustion products at the throat station for the case with no fluid augmentation. Solids flow rate was assumed to remain constant with fluid addition

$$\dot{w}_{\text{solid}} = \rho_t\ (V_t)\ A_t$$

where

ρ_t	density at throat station of all-solid rocket
V_t	velocity at throat station of all-solid rocket
A_t	area of throat station of all-solid rocket

Tankage Volume

The tankage volume of the augmenting fluid is calculated from the following equation:

$$\text{tankage volume} = \frac{\dot{w}_{\text{fluid}}(t_{\text{burn}})}{\rho_{\text{fluid}}} \tag{4}$$

where

$\dot{w}_{\text{fluid}}$	augmenting fluid flow rate
t_{burn}	nominal burn time space shuttle solid rocket booster
ρ_{fluid}	density of augmenting fluid

The density of the augmenting fluid varies with metal loading for the aluminum/liquid hydrogen slurry. A bulk slurry density can be calculated from aluminum and liquid hydrogen densities and mass fractions as follows:

$$\frac{1}{\rho_b} = \frac{X_m}{\rho_m} + \frac{X_f}{\rho_f}$$

where

X_m	weight fraction of aluminum
X_f	weight fraction of liquid hydrogen
ρ_b	bulk slurry density
ρ_m	aluminum density, 2.700 g/cm^3
ρ_f	liquid hydrogen density, 0.071 g/cm^3

Rearranging gives

$$\rho_b = \frac{1}{\dfrac{X_m}{\rho_m} + \dfrac{X_f}{\rho_f}} \tag{5}$$

Thrust

Thrust F corresponding to each quasi-hybrid solid rocket booster concept is determined from the definition of specific impulse

$$I_{sp} = \frac{F}{\dot{w}_{\text{total}}} \tag{6}$$

Therefore,

$$F = I_{sp}(\dot{w}_{\text{total}}) \tag{7}$$

Specific impulse I_{sp} is determined from the CEC program (in units of lbf-sec/lbm) and total flow rate is derived from equation (2).

Appendix C
Rocket Parameters for Quasi-Hybrid Solid Rocket Boosters

TABLE C-I.—ROCKET PARAMETERS FOR LIQUID-HYDROGEN-INJECTED SOLID ROCKET BOOSTER

Liquid hydrogen, wt %	Mass flow rate,[a] kg/sec	Tankage volume, cm^3	Quasi-hybrid thrust, MN
0	0.0	0	9.581
5	204.3	355	11.079
10	431.3	750	11.860
15	685.1	1191	12.697
20	970.5	1688	13.885
25	1294.0	2250	14.912
30	1663.7	2893	15.597
35	2090.3	3635	16.503
40	2588.0	4500	17.650
45	3176.2	5523	18.694
50	3882.0	6750	19.955

[a]Mass flow rate of solids = 3882.0 kg/sec.

TABLE C-II.—ROCKET PARAMETERS FOR LIQUID-HYDROGEN-INJECTED SOLID ROCKET BOOSTER WITH A SOLIDS COMPOSITION CHANGE

Liquid hydrogen, wt %	Mass flow rate, kg/sec	Tankage volume, cm^3	Quasi-hybrid thrust, MN	Liquid hydrogen, wt %	Mass flow rate, kg/sec	Tankage volume, cm^3	Quasi-hybrid thrust, MN
Mass flow rate of solids, 3899.7 kg/sec; 12 wt % aluminum in solid				Mass flow rate of solids, 3927.7 kg/sec; 24 wt % aluminum in solid			
0	0	0	9.617	0	0	0	9.640
5	205.2	357	10.949	5	206.7	359	11.364
10	433.3	753	11.612	10	436.4	759	12.594
15	688.2	1197	12.484	15	693.1	1205	13.471
20	974.9	1695	13.704	20	981.9	1707	14.559
25	1299.9	2260	14.628	25	1309.2	2276	15.704
30	1671.3	2906	15.313	30	1683.3	2927	16.506
Mass flow rate of solids, 3882.0 kg/sec; 16 wt % aluminum in solid				Mass flow rate of solids, 4035.9 kg/sec; 28 wt % aluminum in solid			
0	0	0	9.581	0	0	0	9.577
5	204.3	355	11.079	5	212.4	369	11.348
10	431.3	750	11.860	10	448.4	780	13.161
15	685.1	1191	12.697	15	712.2	1238	14.294
20	970.5	1688	13.885	20	1009.0	1754	15.326
25	1294.0	2250	14.912	25	1345.3	2339	16.453
30	1663.7	2893	15.597	30	1729.7	3008	17.334
Mass flow rate of solids, 3882.0 kg/sec; 20 wt % aluminum in solid				Mass flow rate of solids, 4253.4 kg/sec; 32 wt % aluminum in solid			
0	0	0	9.616	0	0	0	9.647
5	204.3	355	11.264	5	223.9	389	11.793
10	431.3	750	12.152	10	472.6	822	13.852
15	685.1	1191	12.979	15	750.6	1305	15.432
20	970.5	1688	14.123	20	1063.4	1849	16.621
25	1294.0	2250	15.222	25	1417.8	2465	17.723
30	1663.7	2893	15.955	30	1822.9	3170	18.662

TABLE C-II.—Concluded.

Liquid hydrogen, wt %	Mass flow rate, kg/sec	Tankage volume, cm^3	Quasi-hybrid thrust, MN
Mass flow rate of solids, 4418.0 kg/sec; 36 wt % aluminum in solid			
0	0	0	9.670
5	232.5	404	12.085
10	490.9	854	14.268
15	779.6	1356	16.055
20	1104.5	1921	17.372
25	1472.7	2561	18.537
30	1893.4	3292	19.508
Mass flow rate of solids, 4581.7 kg/sec; 40 wt % aluminum in solid			
0	0	0	9.664
5	241.1	419	12.391
10	509.1	885	14.702
15	808.5	1406	16.592
20	1145.4	1992	17.966
25	1527.2	2655	19.205
30	1963.6	3414	20.237

TABLE C-III.—ROCKET PARAMETERS FOR ALUMINUM/LIQUID-HYDROGEN-SLURRY-INJECTED SOLID ROCKET BOOSTER

Liquid hydrogen, wt %	Mass flow rate, kg/sec	Tankage volume, cm^3	Quasi-hybrid thrust, MN
Density of liquid hydrogen, 70.97 kg/m^3; 0 wt % aluminum in slurry			
0	0	0	9.581
5	204.3	355	11.079
10	431.3	750	11.860
15	685.1	1191	12.697
20	970.5	1688	13.885
25	1294.0	2250	14.912
30	1663.7	2893	15.597
35	2090.3	3635	16.503
40	2588.0	4500	17.650
45	3176.2	5523	18.694
50	3882.0	6750	19.955
Density of aluminum/liquid hydrogen slurry, 78.63 kg/m^3; 10 wt % aluminum in slurry			
0	0	0	9.581
5	204.3	321	11.055
10	431.3	677	11.940
15	685.1	1075	12.750
20	970.5	1523	13.847
25	1294.0	2031	15.140
30	1663.7	2611	16.178
35	2090.3	3280	17.095
40	2588.0	4062	18.291
45	3176.2	4985	19.774
50	3882.0	6092	21.333
Density of aluminum/liquid hydrogen slurry, 88.13 kg/m^3; 20 wt % aluminum in slurry			
0	0	0	9.581
5	204.3	286	11.019
10	431.3	604	12.021
15	685.1	959	12.844
20	970.5	1359	13.875
25	1294.0	1812	15.186
30	1663.7	2330	16.559
35	2090.3	2927	17.821
40	2588.0	3624	19.046
45	3176.2	4447	20.577
50	3882.0	5436	22.528
Density of aluminum/liquid hydrogen slurry, 100.25 kg/m^3; 30 wt % aluminum in slurry			
0	0	0	9.581
5	204.3	251	10.971
10	431.3	531	12.076
15	685.1	843	12.956
20	970.5	1195	13.971
25	1294.0	1593	15.212
30	1663.7	2048	16.711
35	2090.3	2573	18.296
40	2588.0	3186	19.903
45	3176.2	3910	21.594
50	3882.0	4778	23.480

TABLE C-III.—Concluded.

Liquid hydrogen, wt %	Mass flow rate, kg/sec	Tankage volume, cm^3	Quasi-hybrid thrust, MN
Density of aluminum/liquid hydrogen slurry, 116.24 kg/m^3; 40 wt % aluminum in slurry			
0	0	0	9.581
5	204.3	217	10.903
10	431.3	458	12.008
15	685.1	727	13.068
20	970.5	1030	14.109
25	1294.0	1374	15.379
30	1663.7	1766	16.869
35	2090.3	2219	18.618
40	2588.0	2747	20.537
45	3176.2	3372	22.307
50	3882.0	4121	24.271
Density of aluminum/liquid hydrogen slurry, 138.30 kg/m^3; 50 wt % aluminum in slurry			
0	0	0	9.581
5	204.3	182	10.815
10	431.3	385	11.944
15	685.1	611	13.104
20	970.5	866	14.223
25	1294.0	1155	15.547
30	1663.7	1484	17.103
35	2090.3	1865	18.852
40	2588.0	2309	20.632
45	3176.2	2834	22.556
50	3882.0	3464	24.698
Density of aluminum/liquid hydrogen slurry, 170.69 kg/m^3; 60 wt % aluminum in slurry			
0	0	0	9.581
5	204.3	148	10.707
10	431.3	312	11.818
15	685.1	495	12.947
20	970.5	702	14.056
25	1294.0	935	15.323
30	1663.7	1203	16.853
35	2090.3	1511	18.524
40	2588.0	1871	20.334
45	3176.2	2296	22.328
50	3882.0	2806	23.891

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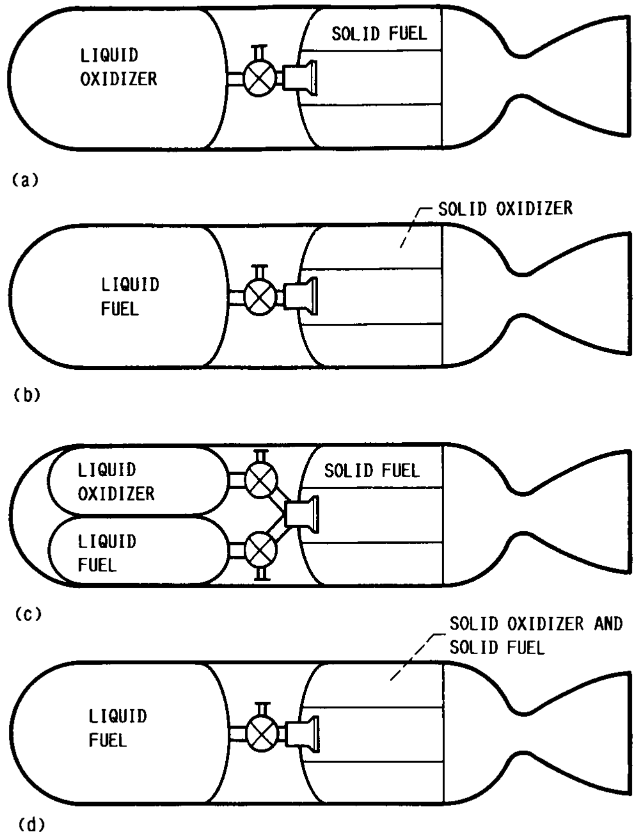
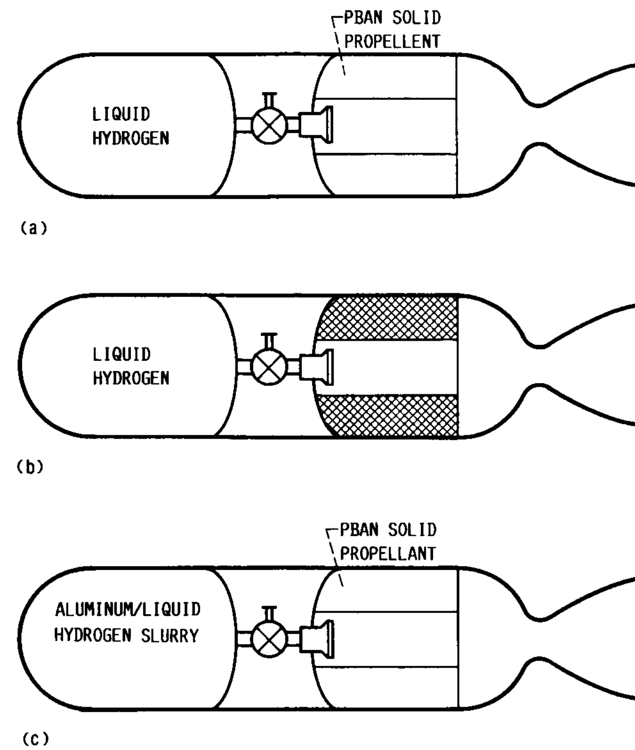


(a) Conventional hybrid rocket.
(b) Reverse hybrid rocket.
(c) Tribrid rocket
(d) Quasi-hybrid rocket.

Figure 1.—Types of hybrid rockets.



(a) Liquid-hydrogen-injected solid rocket booster.
(b) Liquid-hydrogen-injected solid rocket booster with solids composition change.
(c) Aluminum/liquid-hydrogen-slurry-injected solid rocket booster.

Figure 2.—Quasi-hybrid solid rocket booster concepts.

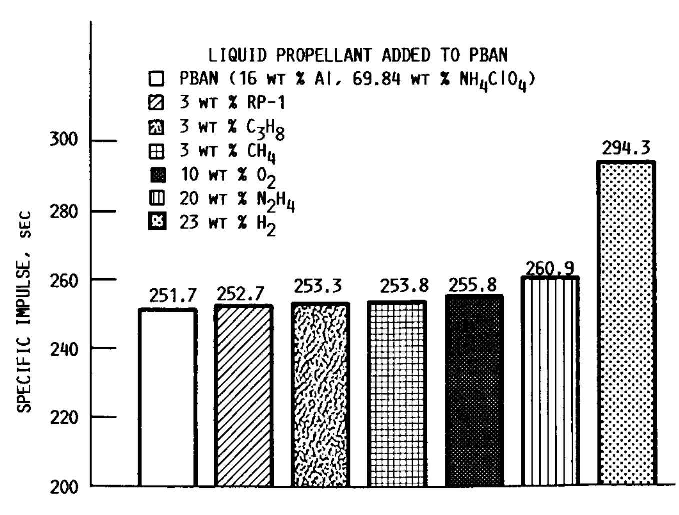


Figure 3.—Peak theoretical specific impulse of PBAN solid propellant with various liquid propellant additions.

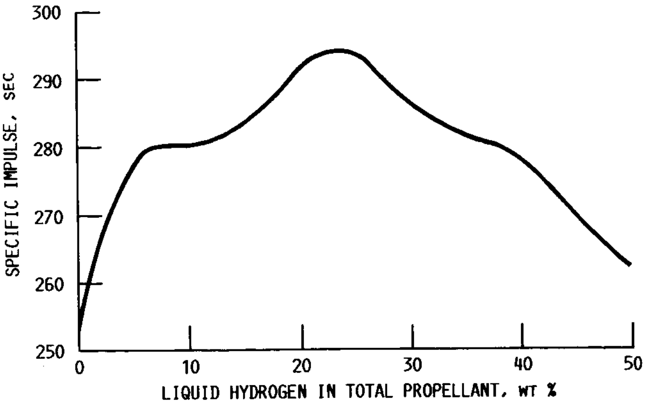


Figure 4.—Theoretical specific impulse of liquid-hydrogen-injected solid rocket booster. Chamber pressure, 4.233 MN/m^2 (614 psia); area ratio, 7.72.

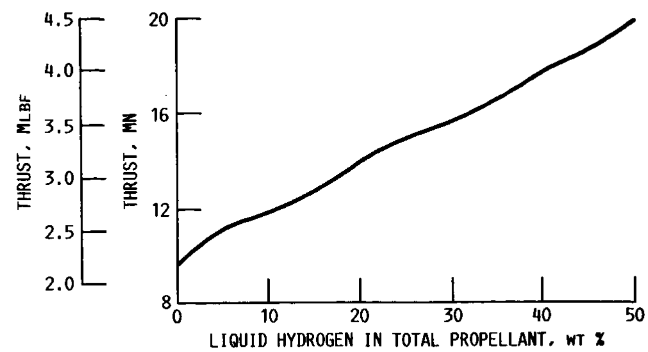


Figure 7.—Thrust of liquid-hydrogen-injected solid rocket booster. Solids mass flow, 3882 kg/sec (8579 lb/sec).

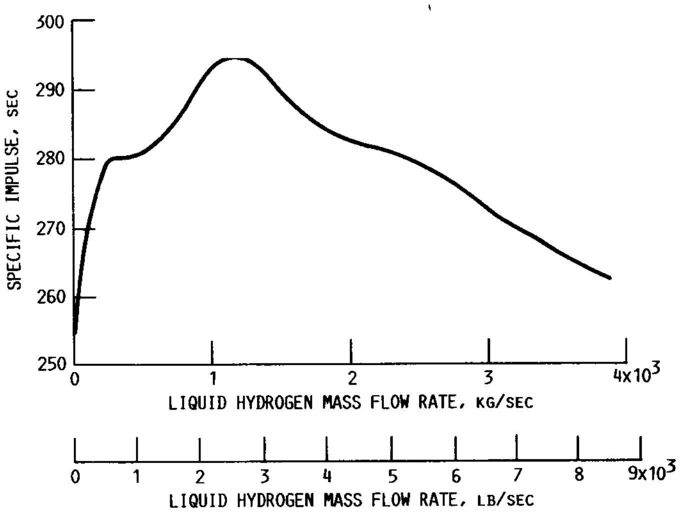


Figure 5.—Mass flow rates for liquid-hydrogen-injected solid rocket booster. Solids mass flow, 3882 kg/sec (8579 lb/sec).

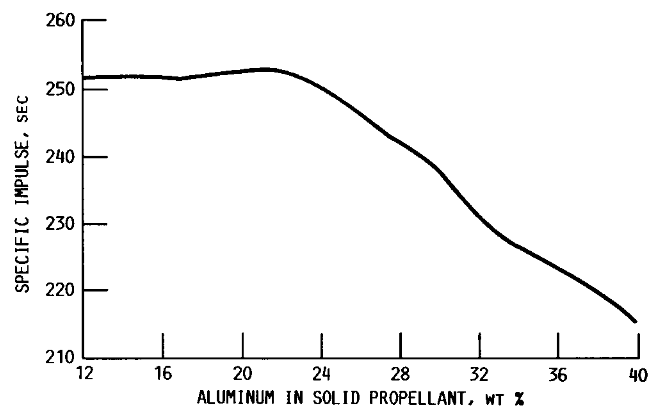


Figure 8.—Theoretical specific impulse of PBAN solid propellant with varying aluminum content. Chamber pressure, 4.233 MN/m^2 (614 psia); area ratio, 7.72; constants: binder, 12.04 wt %; curing agent, 1.96 wt %; catalyst, 0.16 wt %.

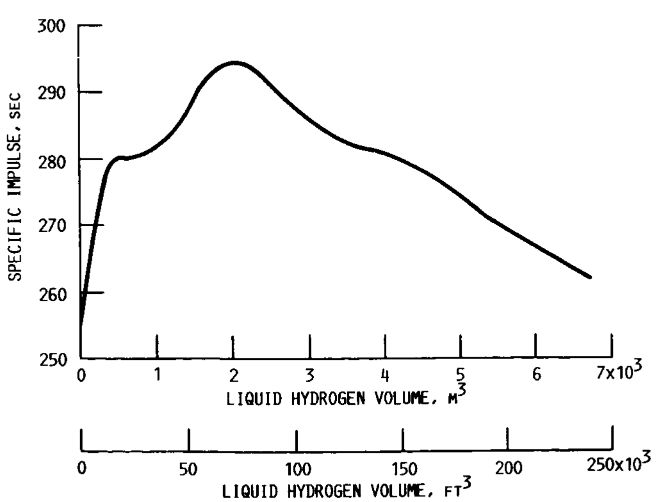


Figure 6.—Tankage volumes for liquid-hydrogen-injected solid rocket booster. Burn time, 123.4 sec.

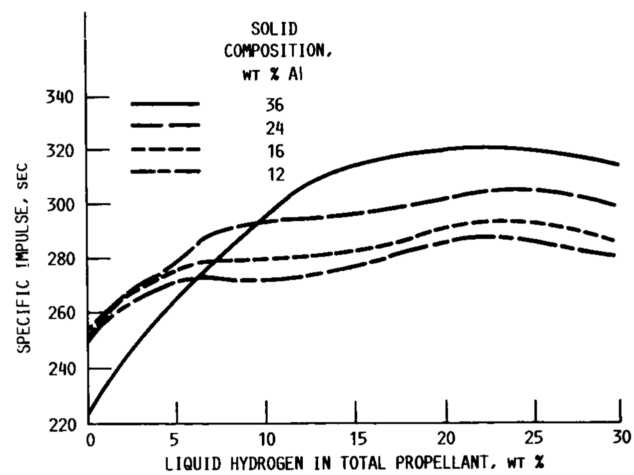


Figure 9.—Theoretical specific impulse of liquid-hydrogen-injected solid rocket booster with solids composition change. Chamber pressure, 4.233 MN/m^2 (614 psia); area ratio, 7.72; constants: binder, 12.04 wt %; curing agent, 1.96 wt %; catalyst, 0.16 wt %.

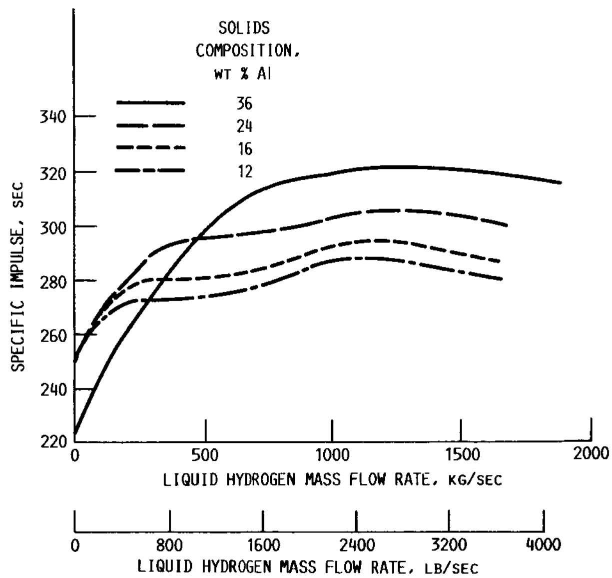


Figure 10.—Mass flow rates for liquid-hydrogen-injected solid rocket booster with solids composition change.

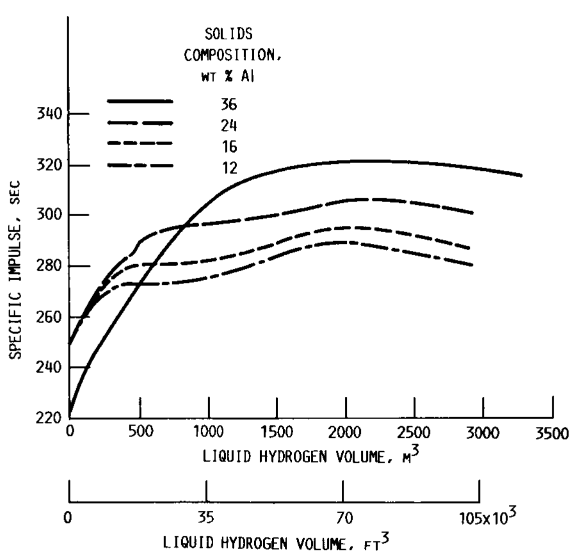


Figure 11.—Tankage volumes for liquid-hydrogen-injected solid rocket booster with a solids composition change. Burn time, 123.4 sec; solids burning rate, 0.93 cm/sec (0.366 in./sec).

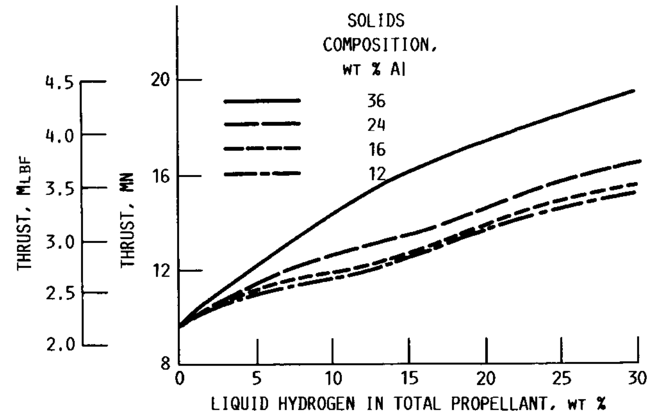


Figure 12.—Thrust of liquid-hydrogen-injected solid rocket booster with solid composition change. Solids burning rate, 0.93 cm/sec (0.366 in./sec).

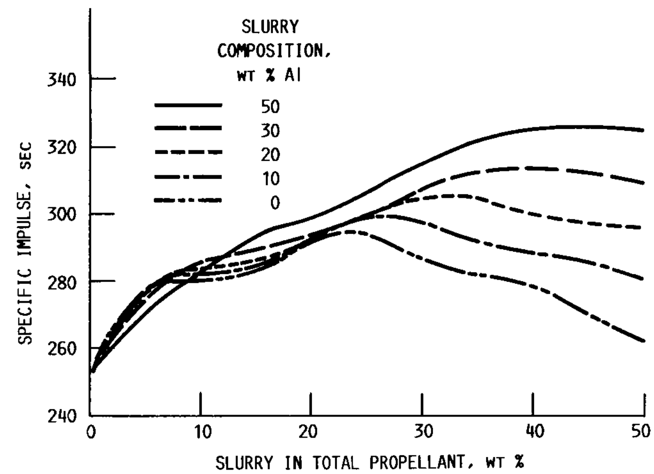


Figure 13.—Theoretical specific impulse of aluminum/liquid-hydrogen-slurry-injected solid rocket booster. Chamber pressure, 4.233 MN/m^2 (614 psia); area ratio, 7.72; PBAN solid propellant composition.

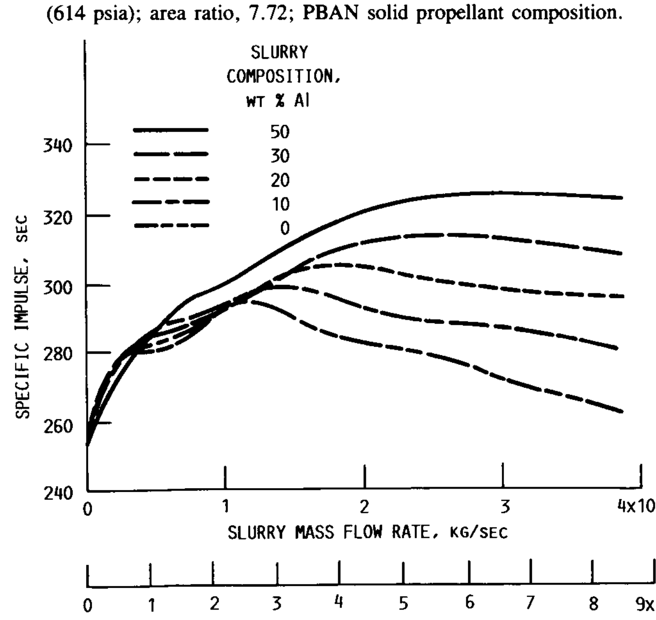


Figure 14.—Mass flow rates for aluminum/liquid-hydrogen-slurry-injected solid rocket booster. Solid mass flow, 3882 kg/sec (8579 lb/sec).

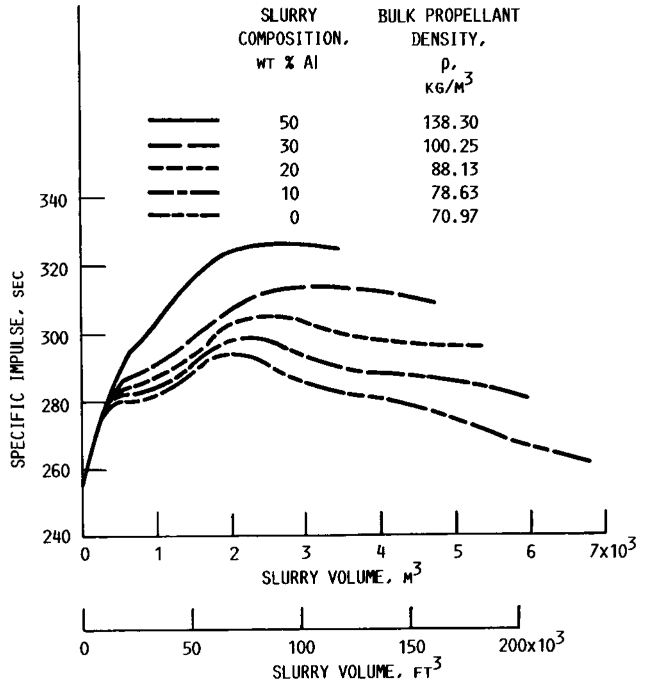


Figure 15.—Tankage volumes for aluminum/liquid-hydrogen-slurry-injected solid rocket booster.

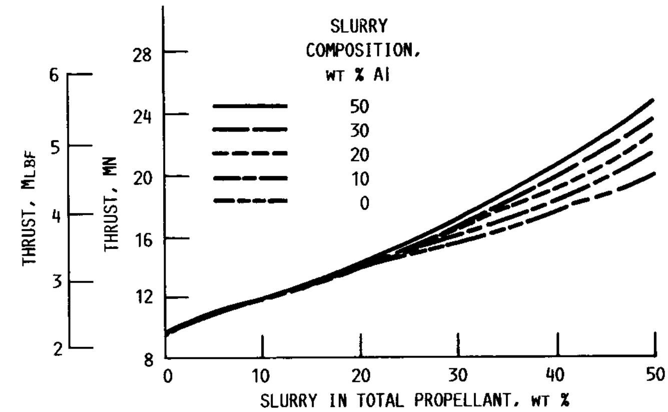


Figure 16.—Thrust of aluminum/liquid-hydrogen-slurry-injected solid rocket booster. Solids mass flow, 3882 kg/sec (8579 lb/sec).

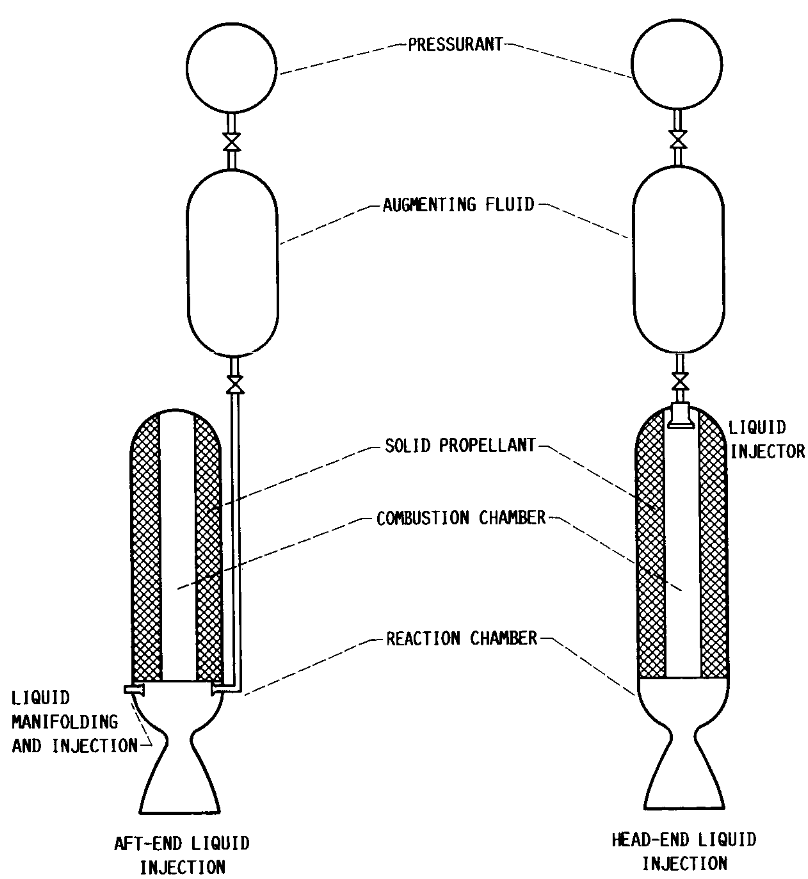


Figure 17.—Injection methods for quasi-hybrid rockets.

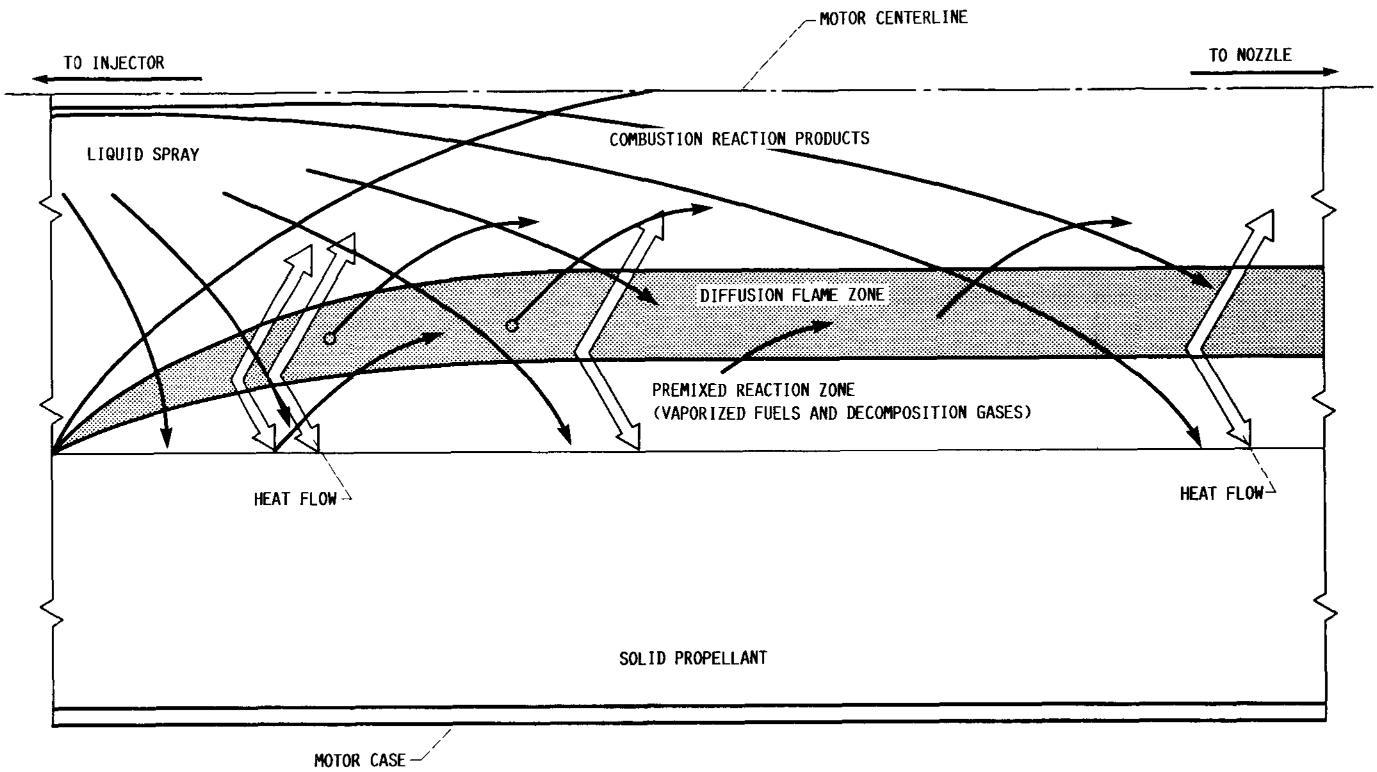


Figure 18.—Hybrid solid propellant combustion.

Report Documentation Page

National Aeronautics and Space Administration

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
NASA TP-2751		

4. Title and Subtitle	5. Report Date
Analysis of Quasi-Hybrid Solid Rocket Booster Concepts for Advanced Earth-to-Orbit Vehicles	August 1987
	6. Performing Organization Code 506-42-11
7. Author(s) Robert L. Zurawski and Douglas C. Rapp	8. Performing Organization Report No. E-3554
	10. Work Unit No.
9. Performing Organization Name and Address National Aeronautics and Space Administration Lewis Research Center Cleveland, Ohio 44135	11. Contract or Grant No.
	13. Type of Report and Period Covered Technical Paper
12. Sponsoring Agency Name and Address National Aeronautics and Space Administration Washington, D.C. 20546	14. Sponsoring Agency Code

15. Supplementary Notes

Prepared for the 23rd Joint Propulsion Conference cosponsored by the AIAA, SAE, ASME, and ASEE, San Diego, California, June 29—July 2, 1987. Robert L. Zurawski, NASA Lewis Research Center; Douglas C. Rapp, Sverdrup Technology, Inc., Lewis Research Center, Cleveland, Ohio 44135. AIAA report number, AIAA-87-2082.

16. Abstract

A study was conducted to assess the feasibility of quasi-hybrid solid rocket boosters for advanced Earth-to-orbit vehicles. Thermochemical calculations were conducted to determine the effect of liquid hydrogen addition, solids composition change plus liquid hydrogen addition, and the addition of an aluminum/liquid hydrogen slurry on the theoretical performance of a PBAN solid propellant rocket. The space shuttle solid rocket booster was used as a reference point. All three quasi-hybrid systems theoretically offer higher specific impulse when compared with the space shuttle solid rocket boosters. However, based on operational and safety considerations, the quasi-hybrid rocket is not a practical choice for near-term Earth-to-orbit booster applications. Safety and technology issues pertinent to quasi-hybrid rocket systems are discussed.

17. Key Words (Suggested by Author(s))	18. Distribution Statement
Hybrid rocket; Quasi-hybrid; Solid rocket booster; Specific impulse; Hydrogen augmentation; Space shuttle	Unclassified – unlimited STAR Category 20

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No of pages	22. Price*
Unclassified	Unclassified	32	A03

NASA FORM 1626 OCT 86

*For sale by the National Technical Information Service, Springfield, Virginia 22161

NASA-Langley, 1987